CALICE Calorimeters: Overview and Highlights

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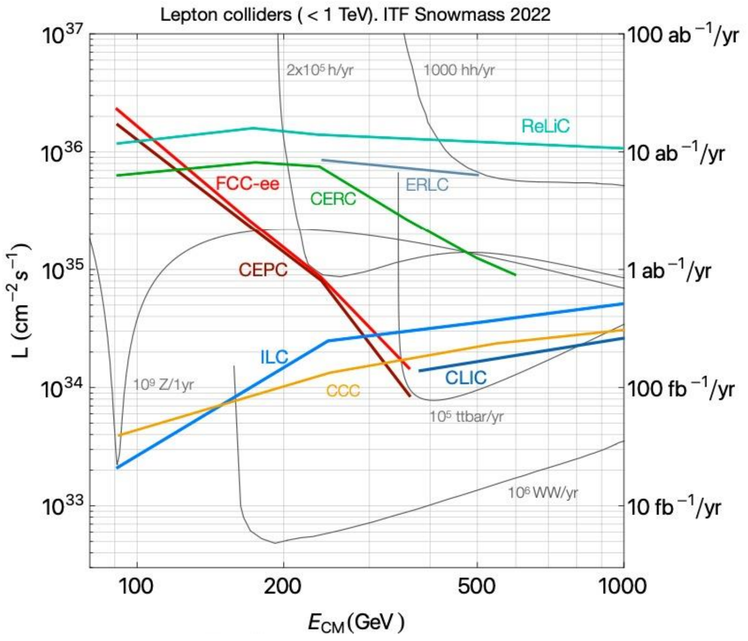
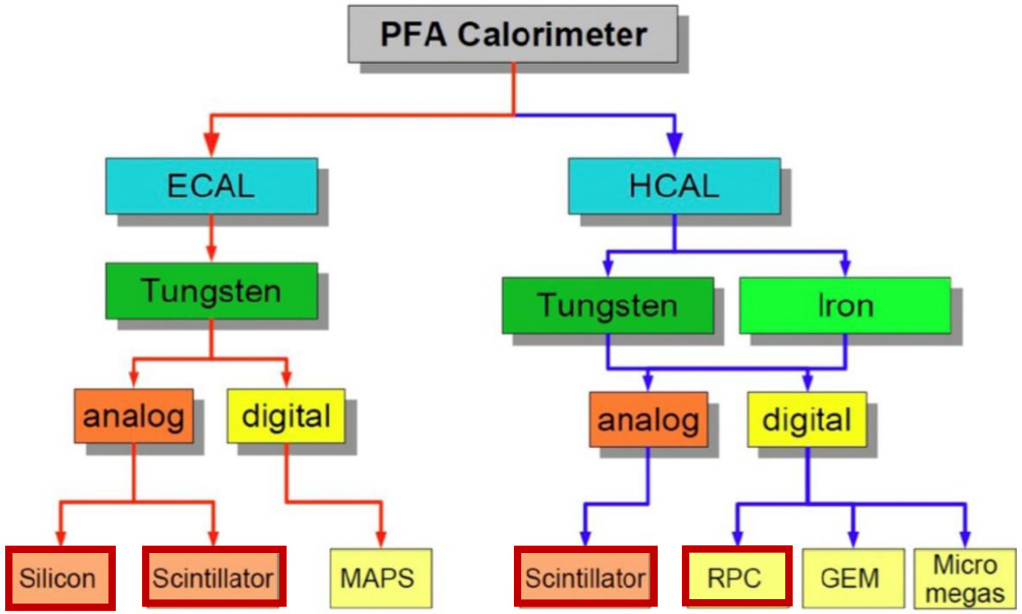
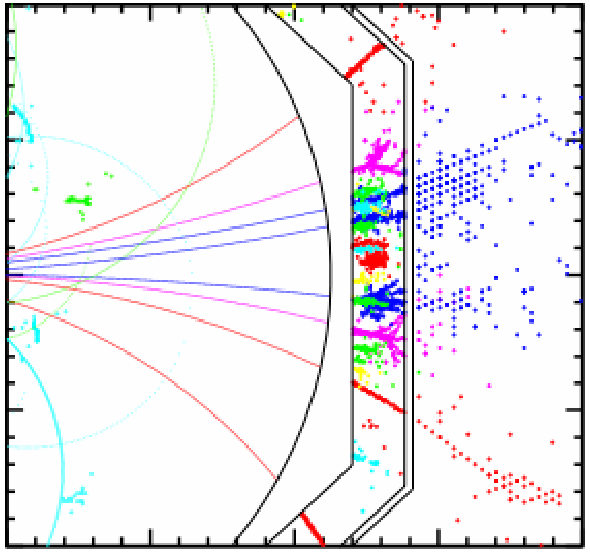
Grateful for input materials from Imad Laktineh (IPNL), Roman Pöschl (IJCLab) and CEPC calorimeter groups

High granularity calorimetry

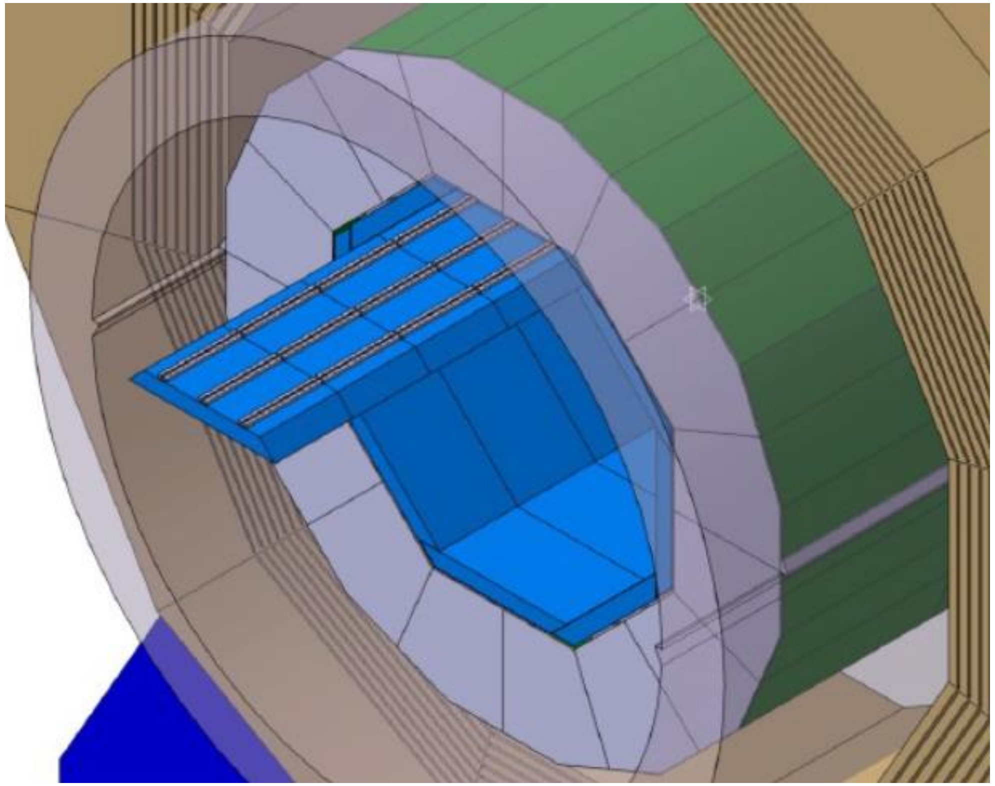




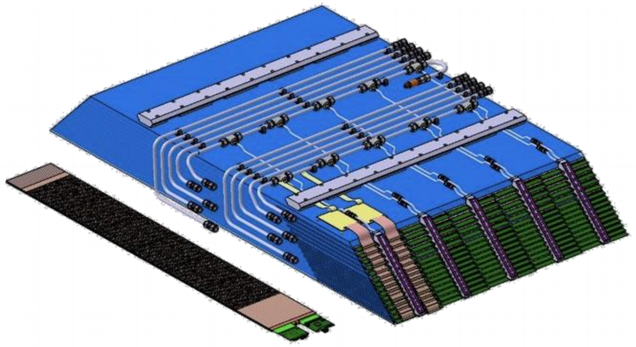


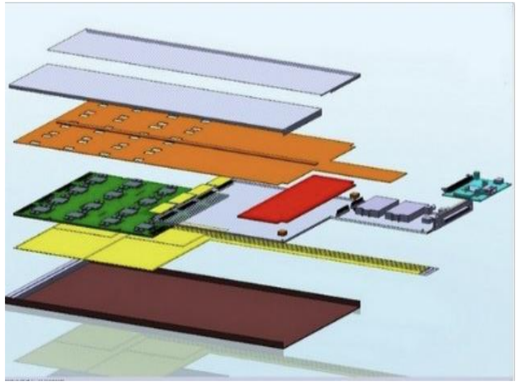
- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry option: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
- Options covered in this talk: silicon, scintillator-SiPM, RPC

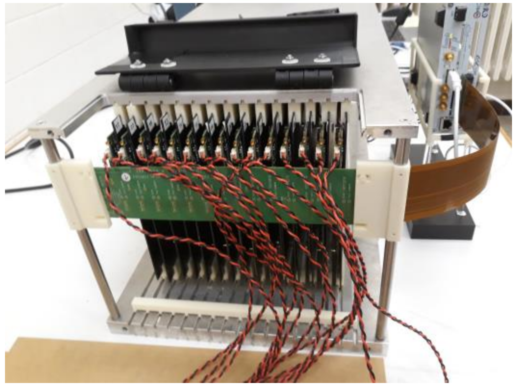
CALICE silicon-tungsten ECAL option



SiW-ECAL: silicon sensors+ CuW





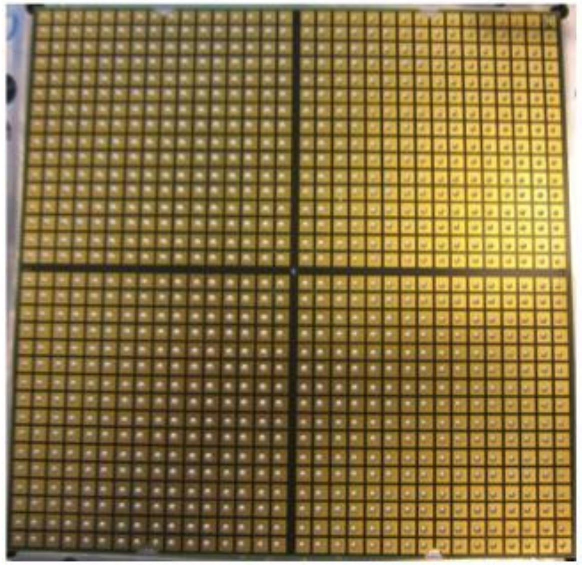


- Tungsten as absorber for narrow showers: better separation capability
- Silicon as sensitive layers: allows pixelization required by high granularity
- Very compact design: thickness of **20 cm for ~30 Si-W layers in 24X0**
  - Leading to limited space for readout boards and electronics components

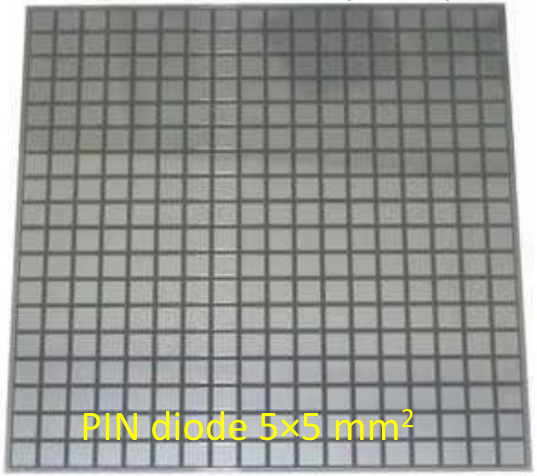
SiW-ECAL prototype

PCB with electronics (upside)

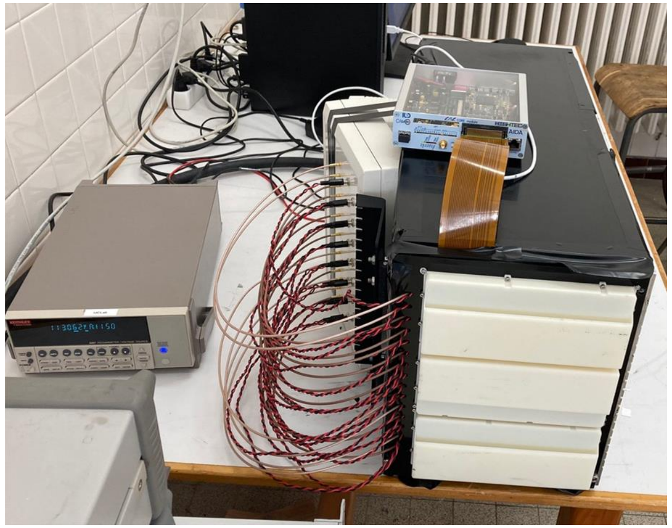
PCB with readout pads (downside)

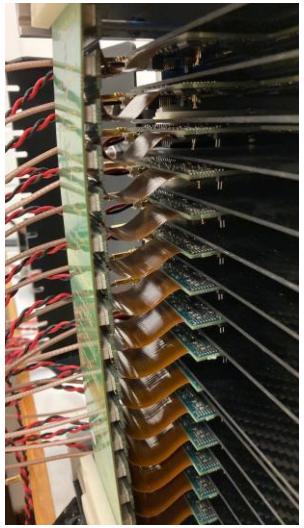


Silicon sensor with square pads



Use conductive glue (epoxy + silver): no space for wire-bonding

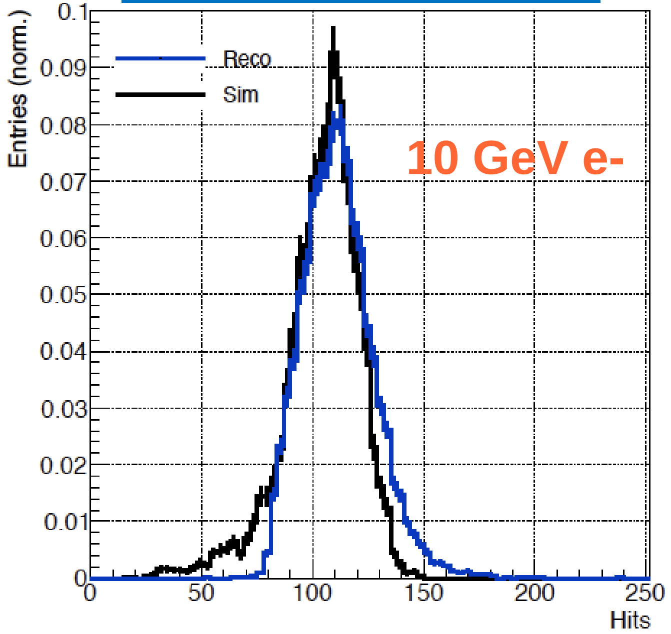




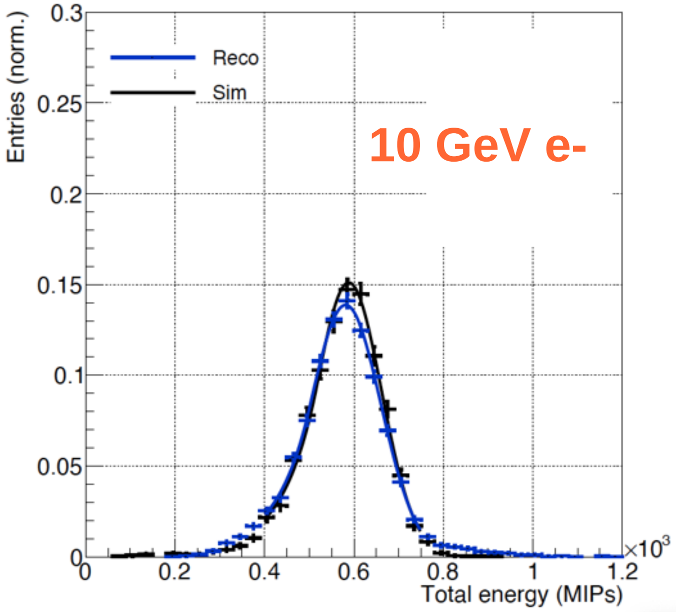
- Tower of 15 short layers ($18\times18 cm^2$)
  - Longitudinal depth $21X_0$
  - 15,360 readout cells in total
  - Overall size of $640\times304\times246\ mm^3$
- Commissioned in 2020-2022
- Beamtests in November 2021 and during 2022
  - Mainly technical tests but also first real showers

SiW-ECAL beamtests and data analysis

Total number of hits

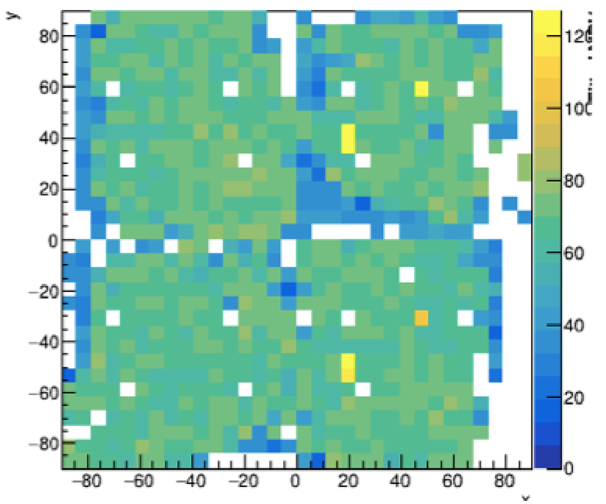


Total energy (in MIPs)

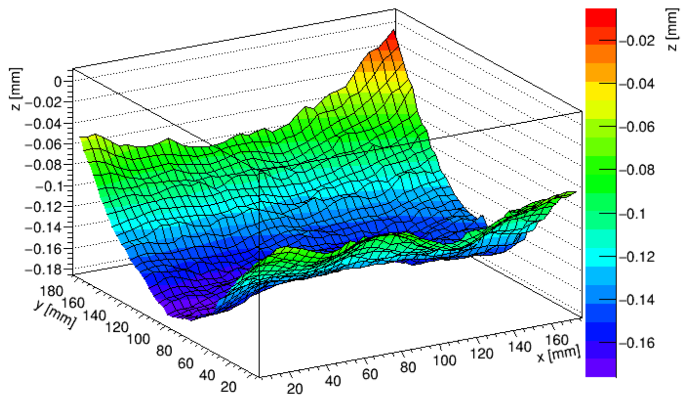


- Reasonable agreement between data and MC: #hits, energy
- Energy resolution in ballpark expected from simulation
- More analysis work required (including combined analyses)

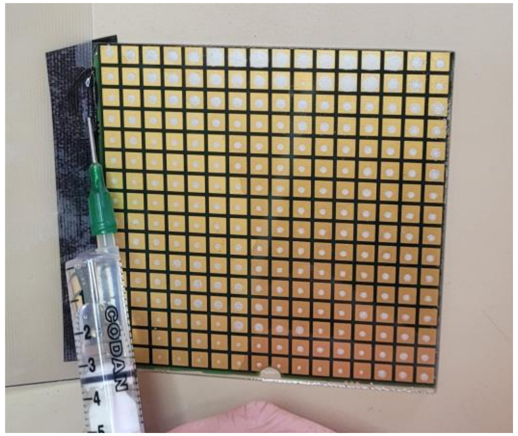
R&D to address a critical issue: sensor delamination



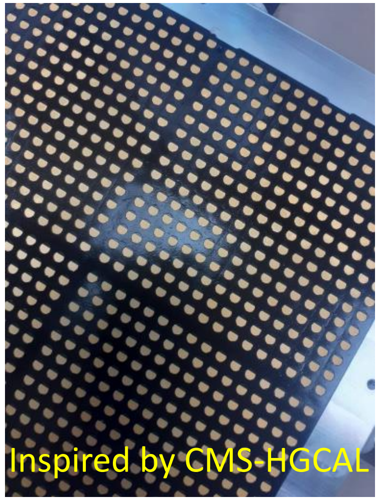
Control of PCB deformation



Underfill

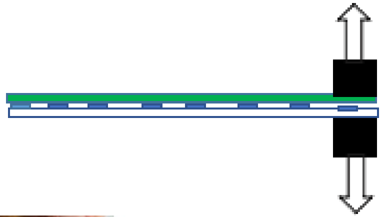


Double-sided tape



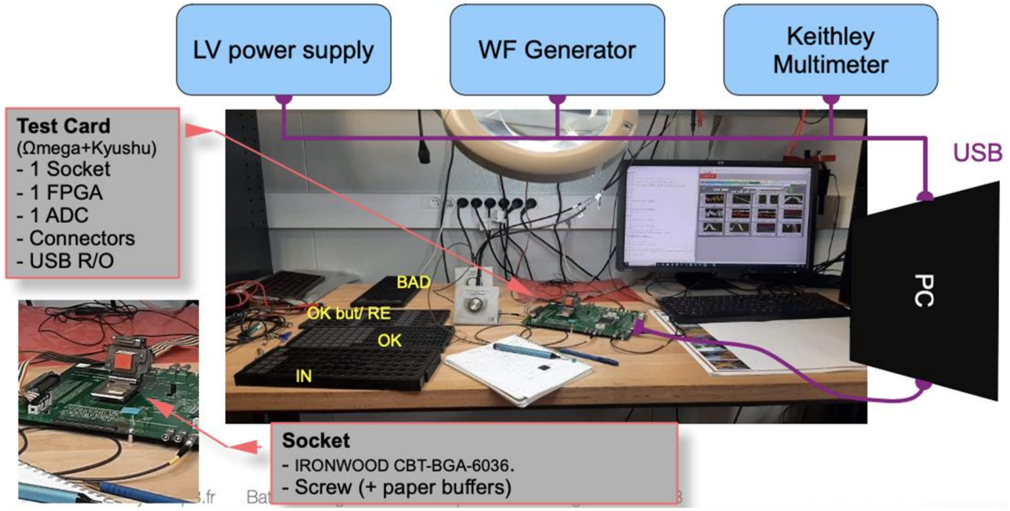
- Sensor connectivity degradation: inhomogeneous response
  - Partially no response, esp. at wafer boundaries
  - Visual inspection and electrical tests confirmed sensor delamination from the PCB → glue dots have failed
- PCB deformation: possibly the major reason (ongoing studies)
  - PCB shape control: e.g. heating, humidity control (drying out)
- Low-viscosity glue with an extra curing step (at 80°C) → mechanical tests
- Alternative hybrid option: with double-sided tape (250um, perforated)

Tensile tests

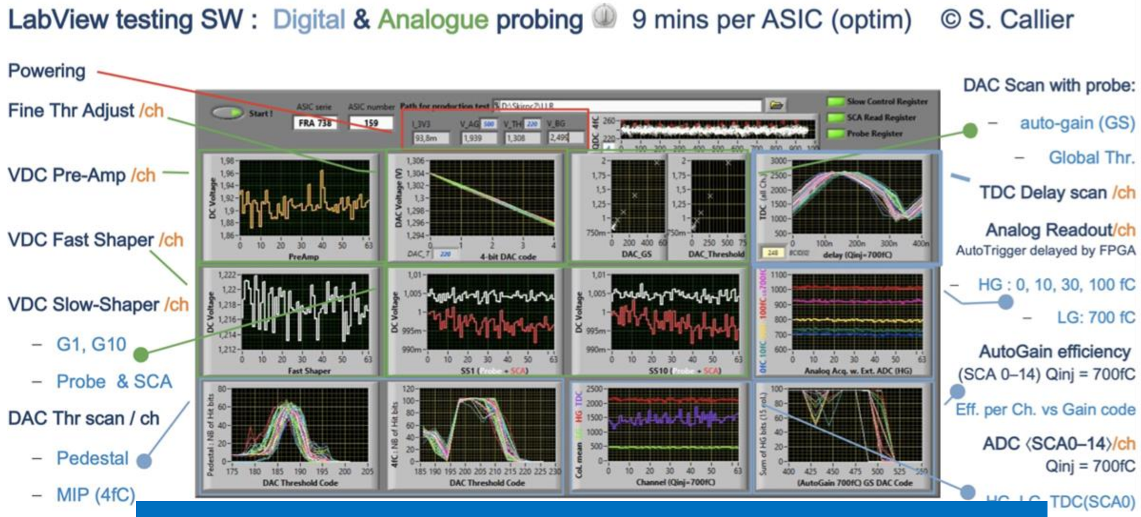


New developments in 2023

SKIROC testbench at LLR

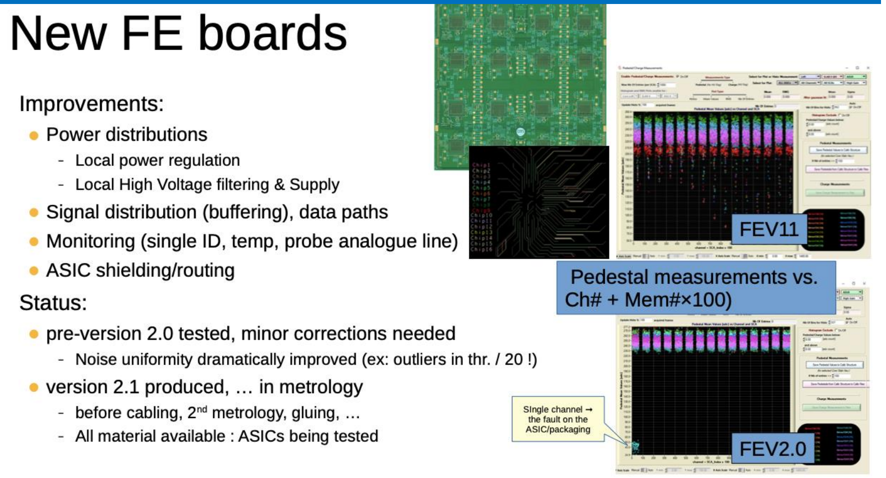


Test protocol developed by OMEGA



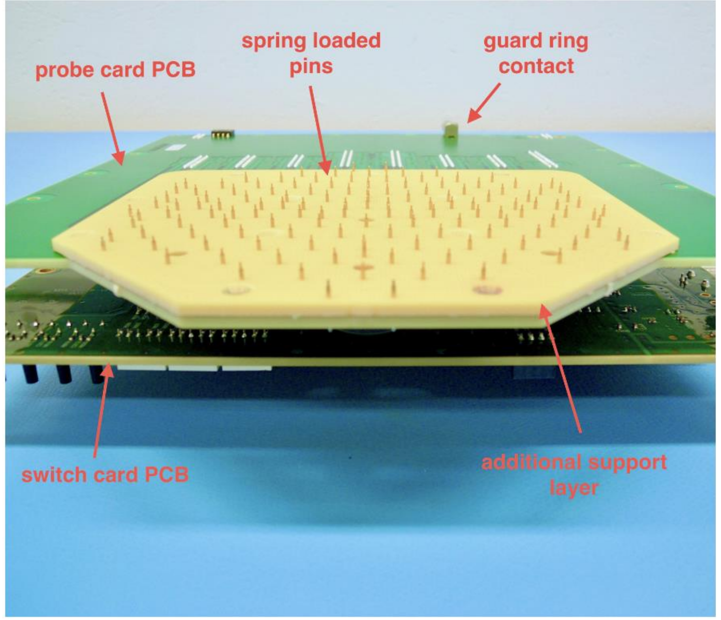
- ASIC (SKIROC) tests
  - 151/400 SKIROCs tested, with a satisfactory yield
  - Expected enough for 9 layers of 18×54 cm^2 (TBD)
- New front-end boards
  - Improvements in power and signal distributions, ASIC shielding and routing
  - Plan to build 15-layer stack based on these new boards

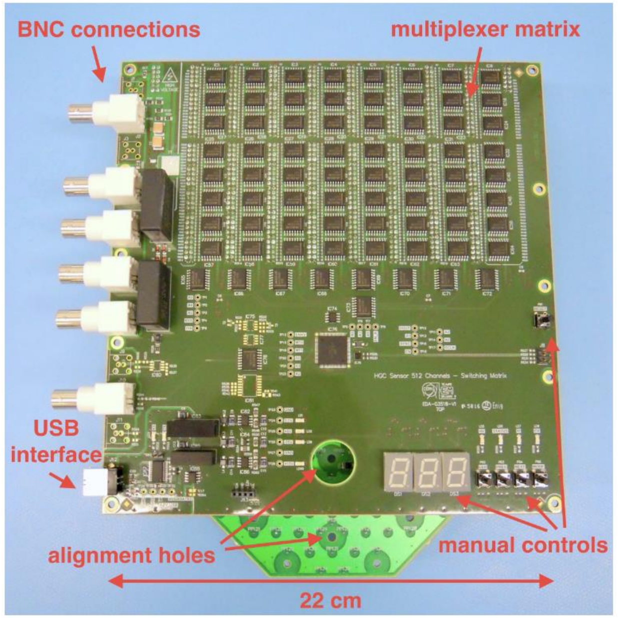
New front-end PCBs (LLR, IJCLab, LPNHE, OMEGA)



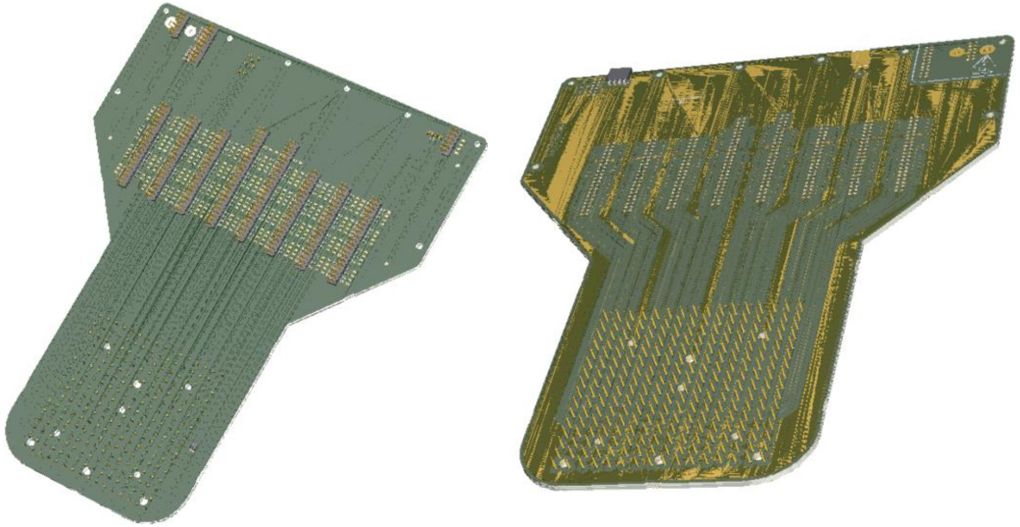
Silicon sensor characterisation

"ARRAY" System in CMS-HGCAL project

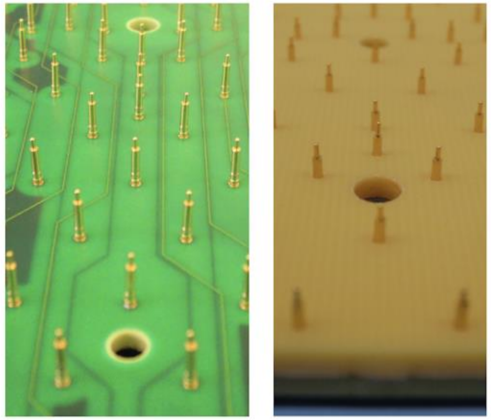




New CALICE SiW-ECAL 6-inch 256-cell probe card

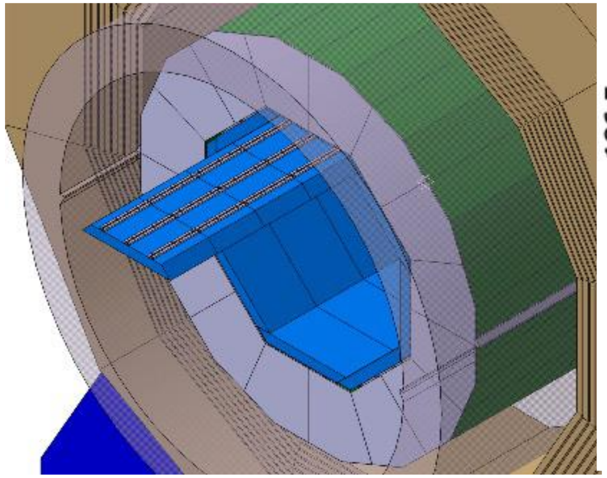


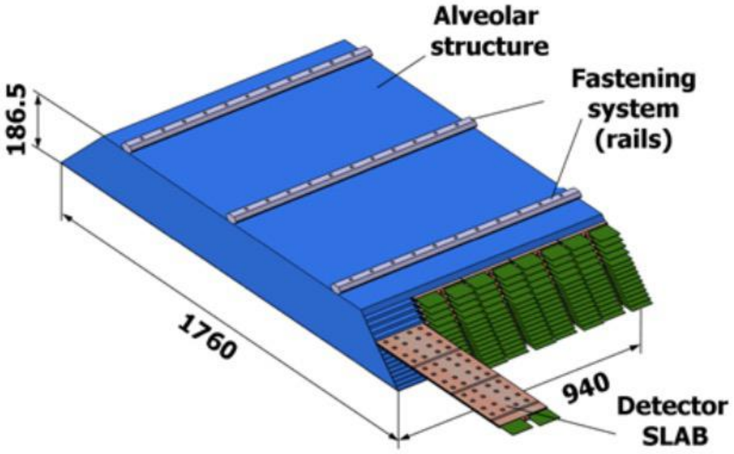
Spring loaded, gold plated pins

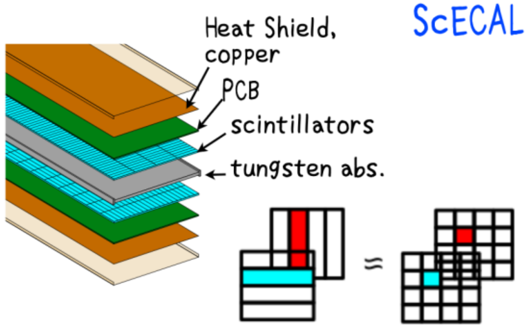


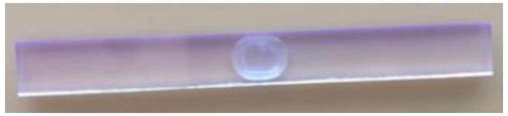
- Silicon sensor characterisations
  - Crucial in prototyping phase and for quality control in mass production (IV, CV, V_{BD}, V_{FD}, C_{FD})
- Bias all pads (by a probe card) and switch between pads (switch a matrix)
  - Measurements with accuracy of o(100pA) and few pF for unirradiated samples
- New probe card adapted to CALICE SiW-ECAL sensor layout

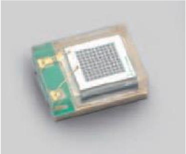
CALICE scintillator-tungsten ECAL option

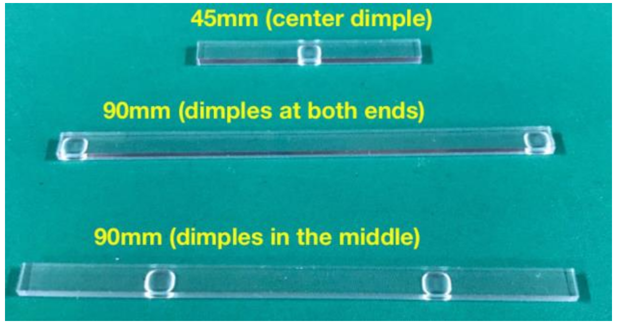


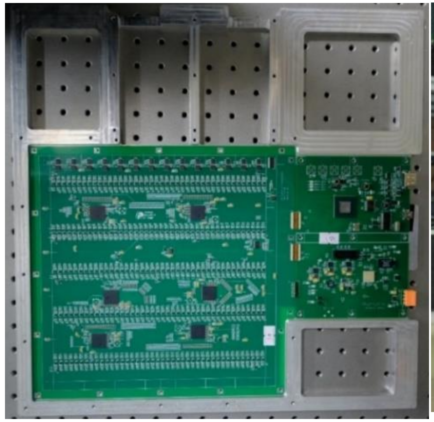










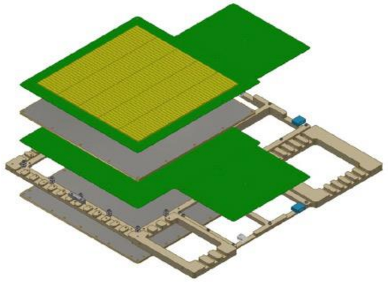


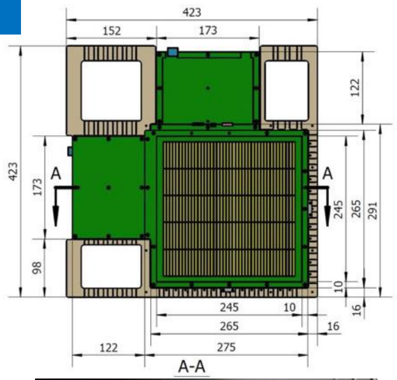
- ScW-ECAL: scintillator strips with SiPM readout + CuW absorber
  - A cost-effective option with plastic scintillator and less readout channels than SiW-ECAL
  - Effective transverse granularity of $5 \times 5\text{mm}^2$
  - Pattern recognition issue ("ghost hits"): to be addressed by the "Strip-Splitting" Algorithm
- ScW-ECAL technological prototype: developed in 2016-2020

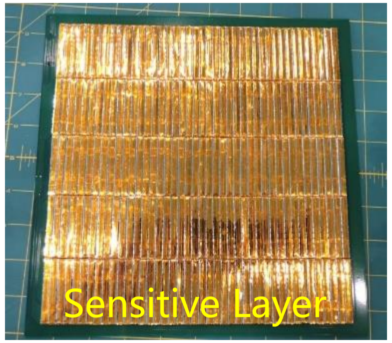
ScW-ECAL technological prototype

ScW-ECAL tech. prototype

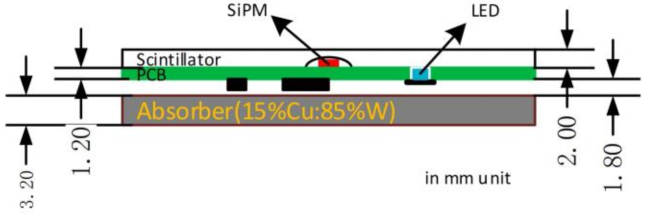
"Super-layer" design



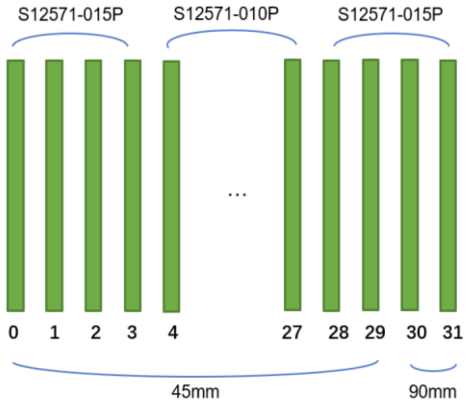


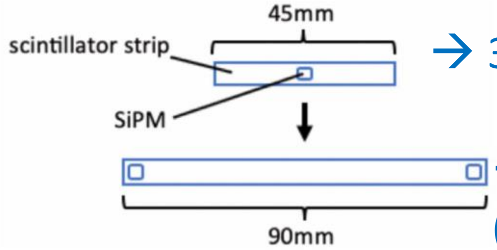


Scintillator-SiPM readout scheme



Sensitive layer arrangements





→ 30 sampling layers

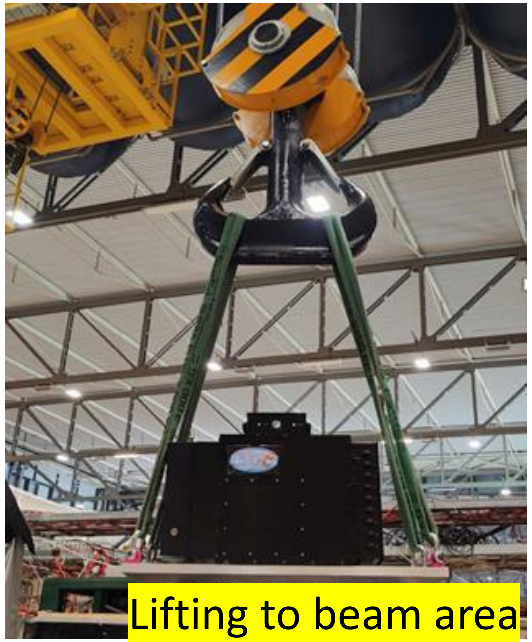
→ 2 sampling layers (in the rear part)

- ScW-ECAL prototype: developed in 2016-2020
  - Transverse area of ~22x20 cm, 32 longitudinal sampling layers
  - 6,720 channels, ~350 kg, SPIROC2E (192 chips)
- Beamtest campaigns at CERN in 2022-2023
  - Along with AHCAL prototype

ScW-ECAL beamtests at CERN

Oct 19 – Nov 2, 2022	Apr 26 – May 10, 2023	May 17 – 31, 2023
SPS H8 beamline	SPS H2 beamline	PS T9 beamline

Transportation

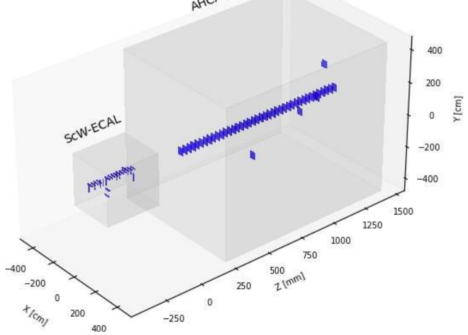


Lifting to beam area

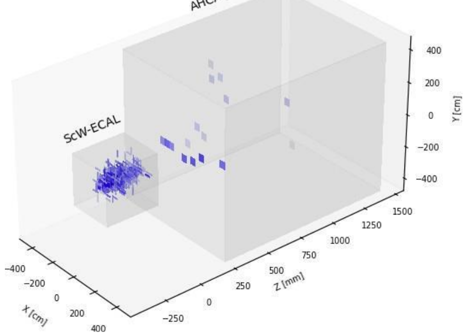
Prototype assembly on site

ScW-ECAL fixed on platform

100GeV muon

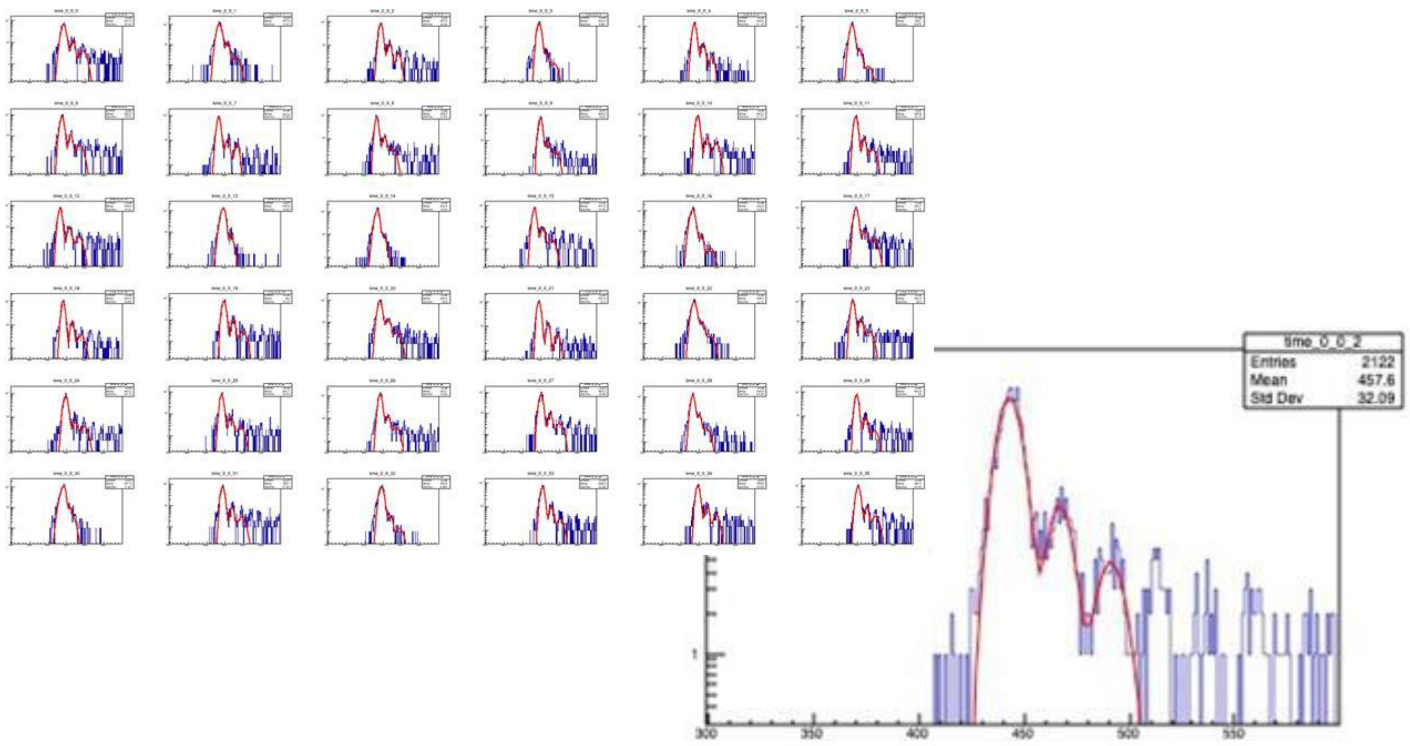


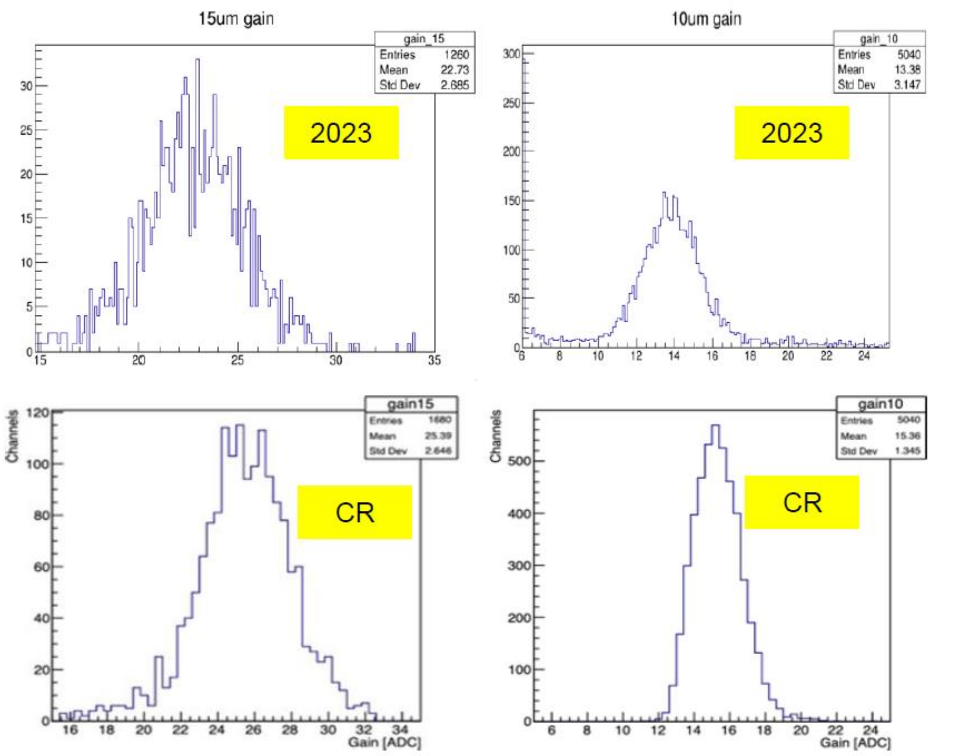
60GeV electron



- Decent statistics of testbeam data samples collected
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 GeV at SPS
  - Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS

ScW-ECAL: SiPM calibrations with LED data



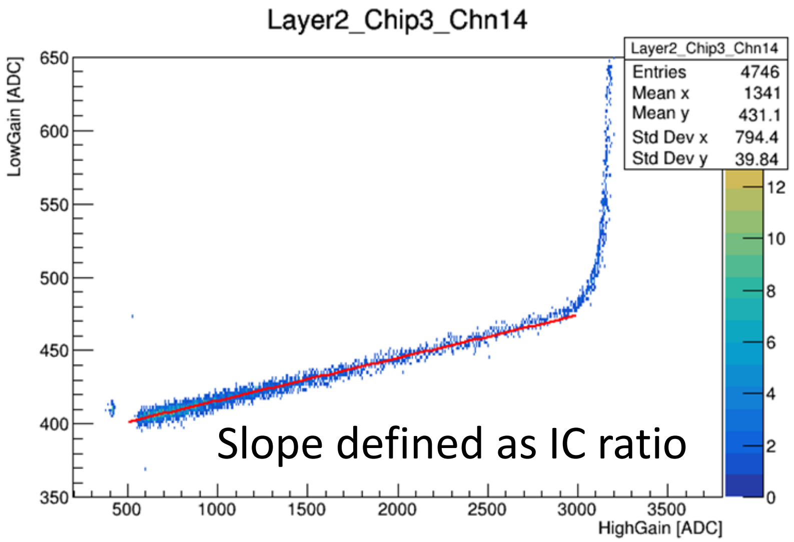


- LED data for SiPM gain calibrations
  - On-board LEDs: calibration data taken during beam tests
  - SiPM gain: single photon calibration done for each channel (25-29°C)
  - Comparisons made with previous long-term cosmic-ray data (20°C)

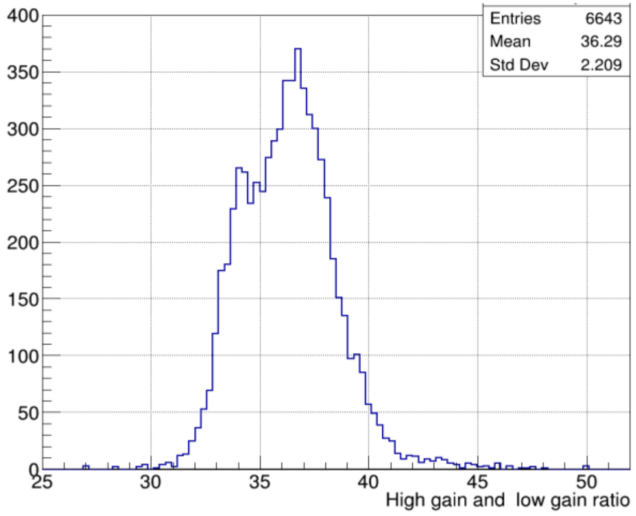
Increased bias voltage (+0.5V) of all channels during beam tests to compensate temperature difference from CR test

ScW-ECAL data analysis: IC calibration

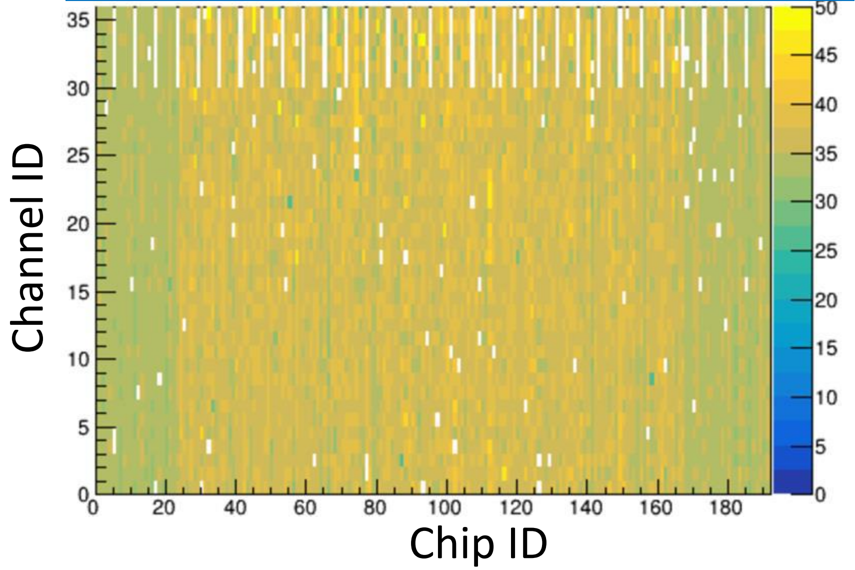
HG ADC versus and LG ADC



Intercalibration Ratio

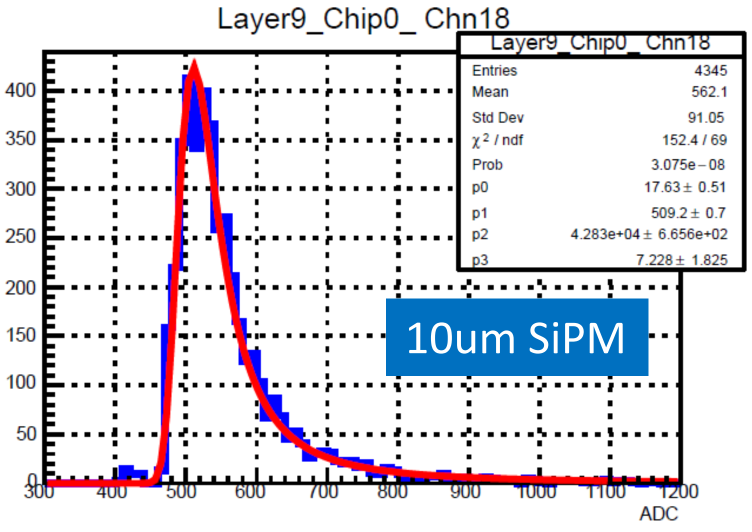


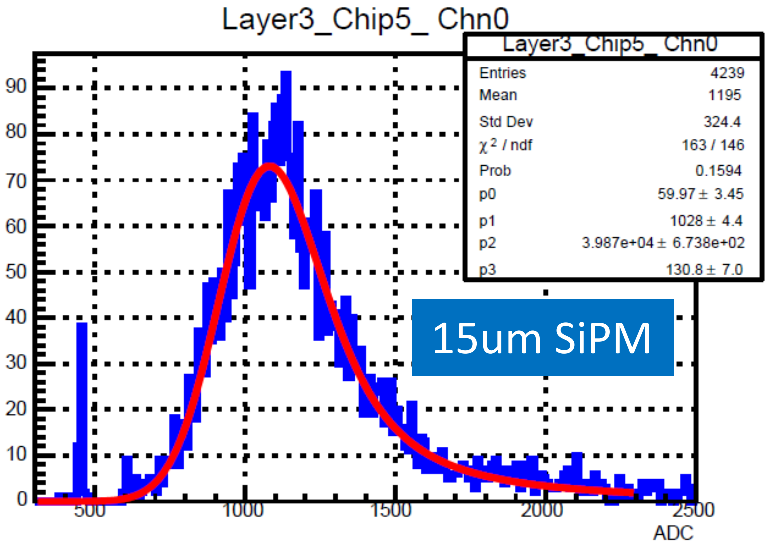
Intercalibration Ratio: ChipID vs ChnID

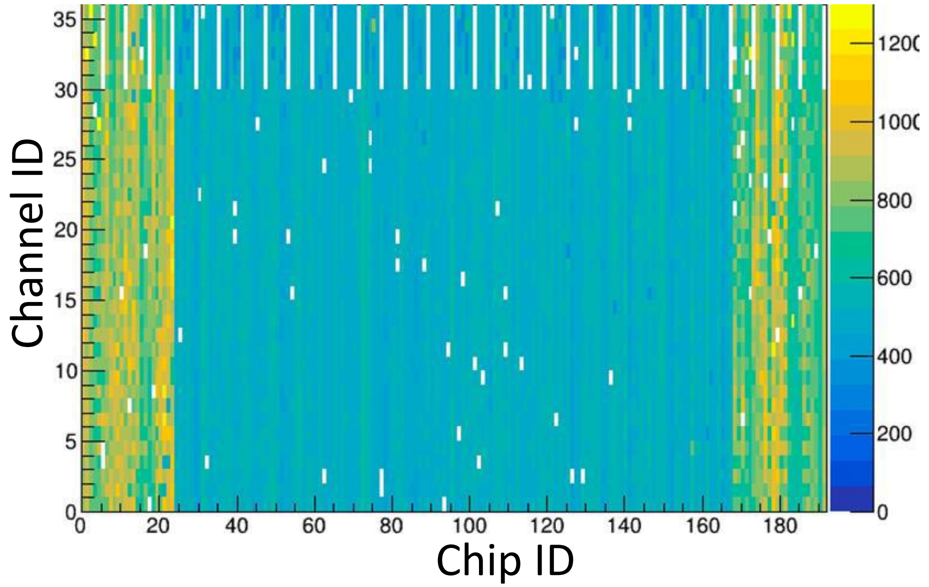


- Intercalibration (IC) ratio of High Gain (HG) and Low Gain (LG)
  - SPIROC2E chip has two gain modes to cover a large dynamic range
  - HG ADC saturation position: dependent on channels and chips
  - Also need to determine valid LG range (channel/chip-wise calibrations)

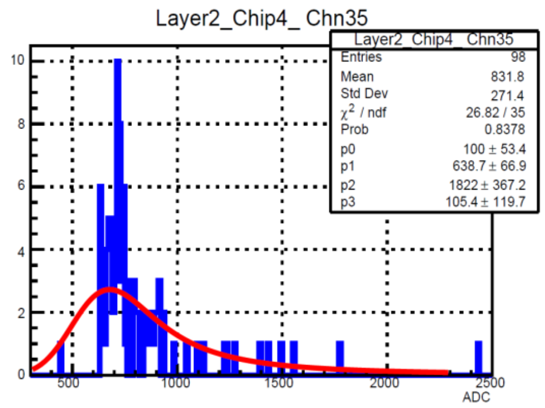
ScW-ECAL data analysis: MIP calibration



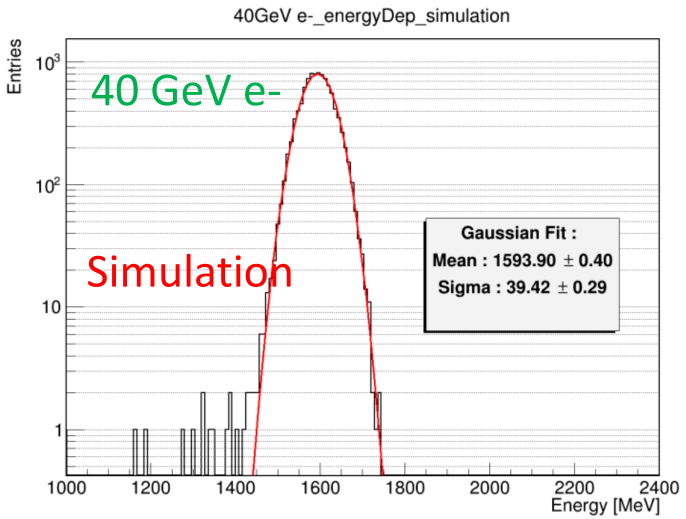


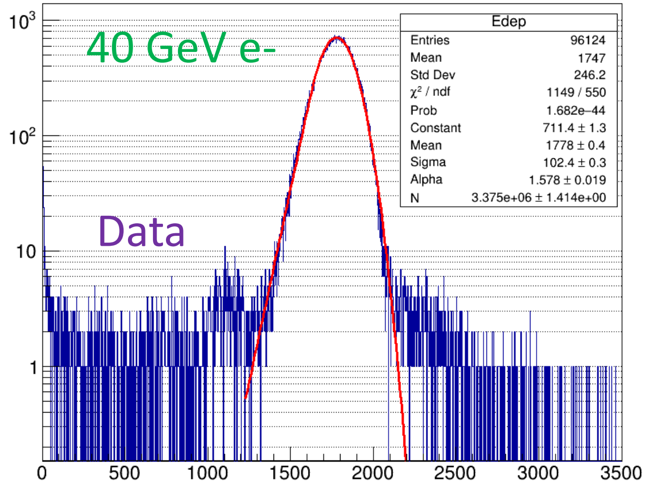


- MIP calibration with 100 GeV muon data
  - Extracted MPV value from Landau distribution convoluted with Gaussian
  - Trigger threshold and SiPM bias voltage optimized
  - Muon tracking algorithm applied to improve fitting quality
  - A small fraction of channels failed, due to insufficient statistics

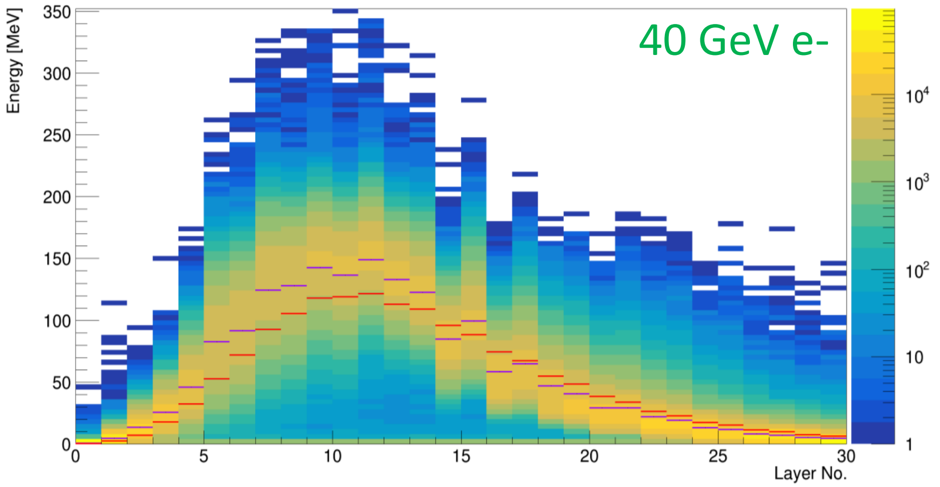


ScW-ECAL electron data: EM shower studies



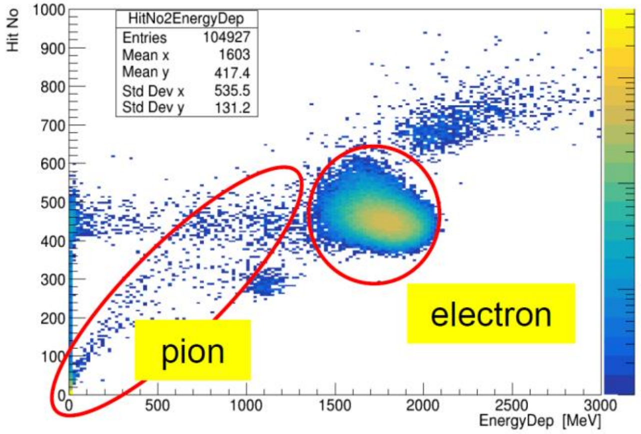


Longitudinal Shower Profile: MC vs Data

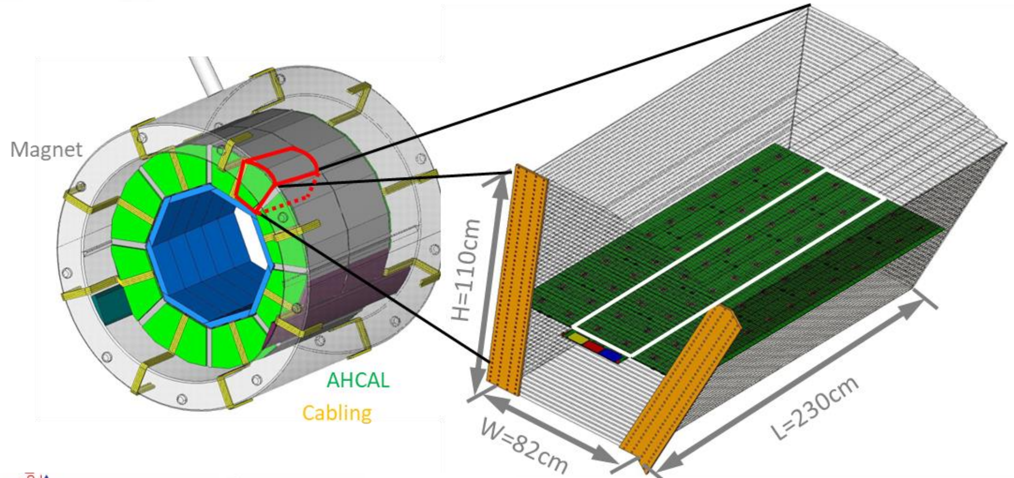


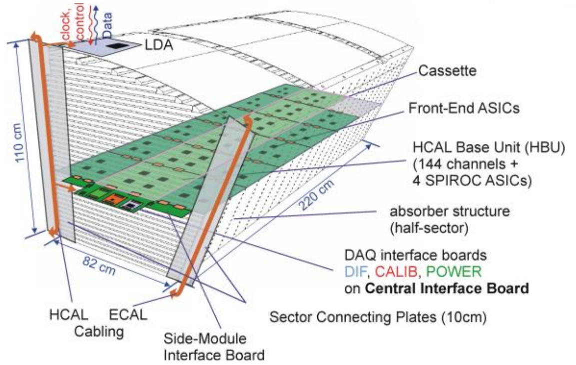
- Simulation including digitisation: photon fluctuations, trigger or energy threshold (0.5 MIP), SiPM saturation
- Still discrepancy in MC/data: energy response, shower profile
- Observed contamination from pions
- Ongoing efforts: simulation + digitisation, PID for better purity, impacts of SiPM noises

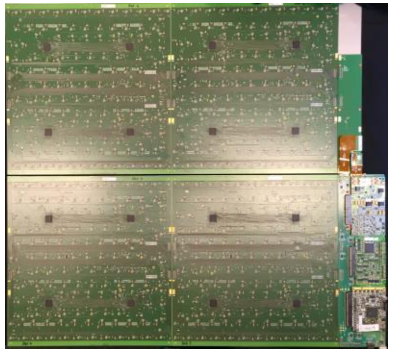
Energy vs Hit Number

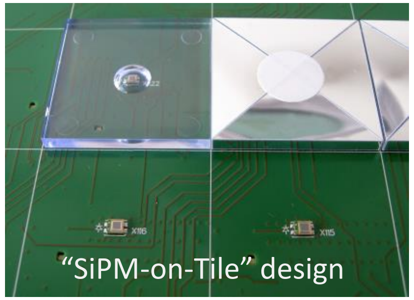


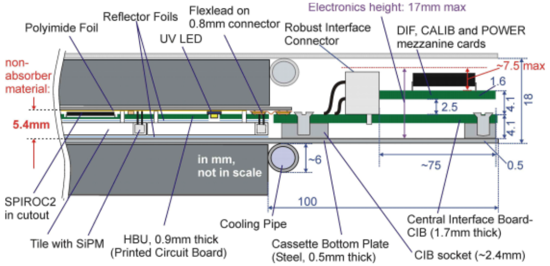
Scintillator-Steel HCAL (AHCAL)





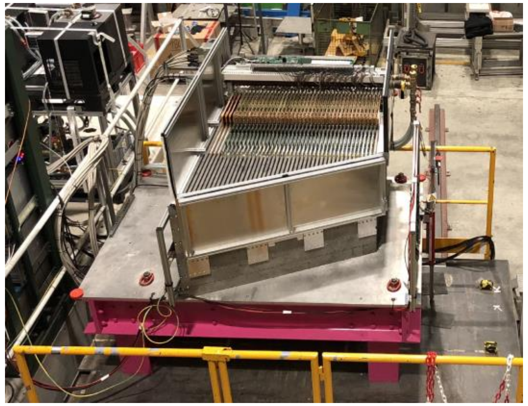




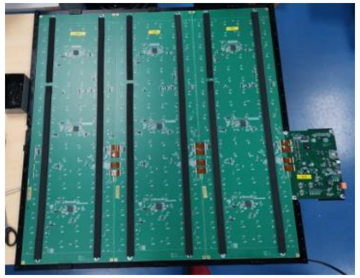


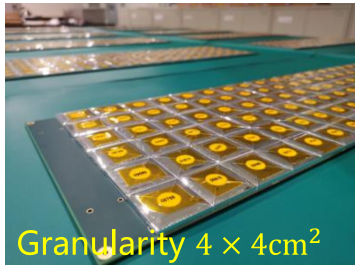
Analogue HCAL prototype: scintillator tile +SiPM, steel

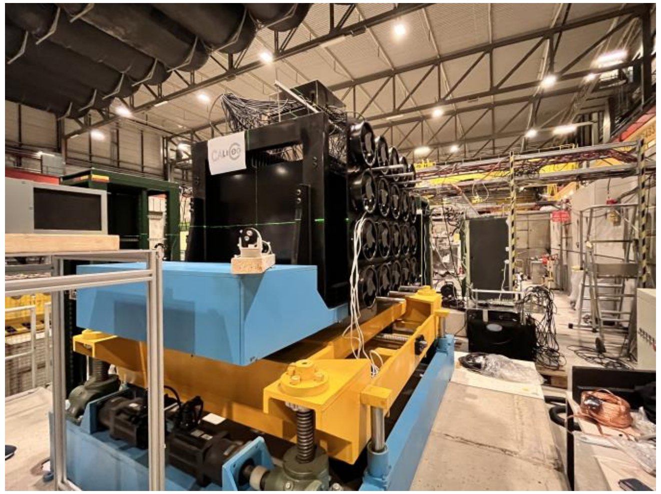
2023 JINST 18 P11018



- AHCAL tech. prototype (2010-2017)
- Transverse 72x72 cm^2, 38 layers (4.4λ_I)
- 22,000 channels (3×3 cm^2 tiles)







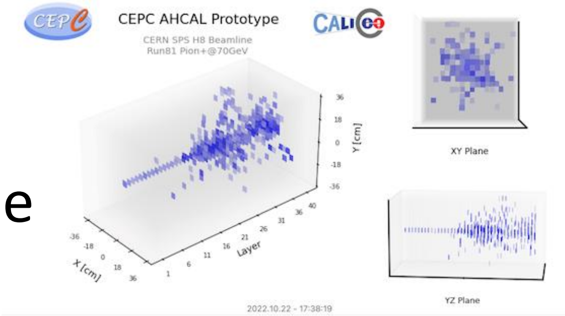
- CEPC-AHCAL prototype (2018-2022)
- Transverse 72x72 cm^2, 40 layers
- 12,960 channels (4×4 cm^2 tiles)

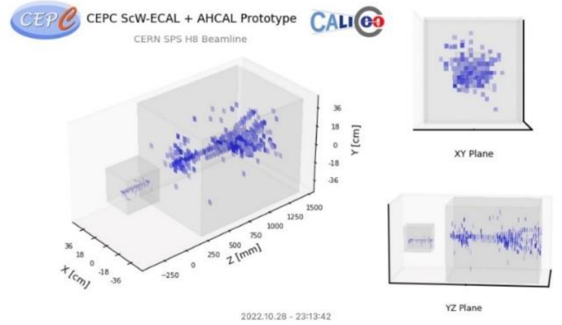
CEPC-AHCAL prototype: CERN beamtests

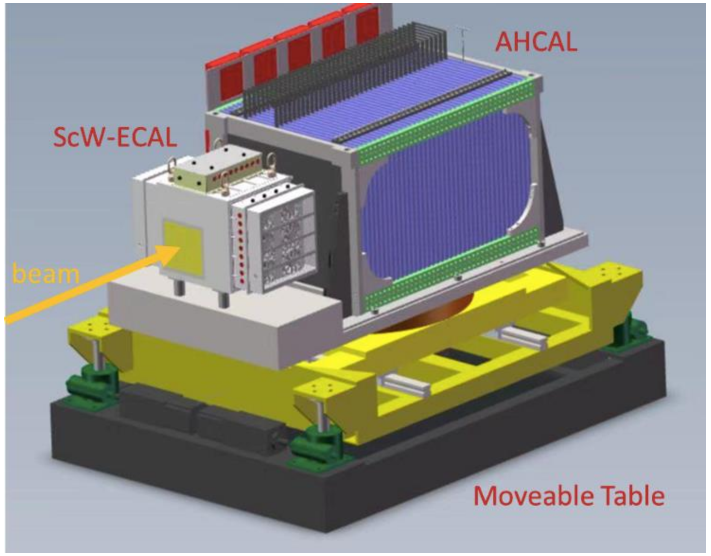
Oct 19 – Nov 2, 2022	Apr 26 – May 10, 2023	May 17 – 31, 2023
SPS H8 beamline	SPS H2 beamline	PS T9 beamline

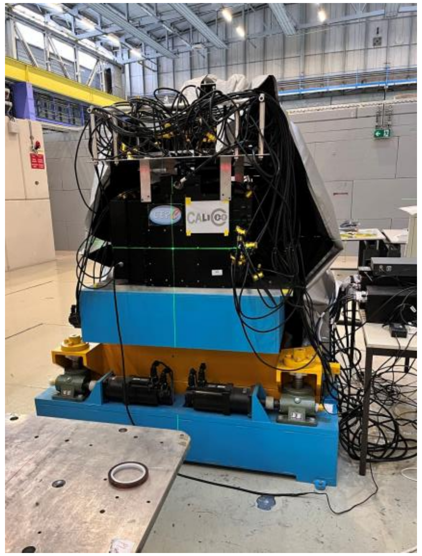
- Decent statistics of testbeam data samples: w/wo ScW-ECAL prototype
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 GeV at SPS
  - Pions: 1 – 15 GeV at PS, 10 – 120 GeV (also 150 – 350 GeV) at SPS

→Overlapped energy points (10-15 GeV) at PS and SPS





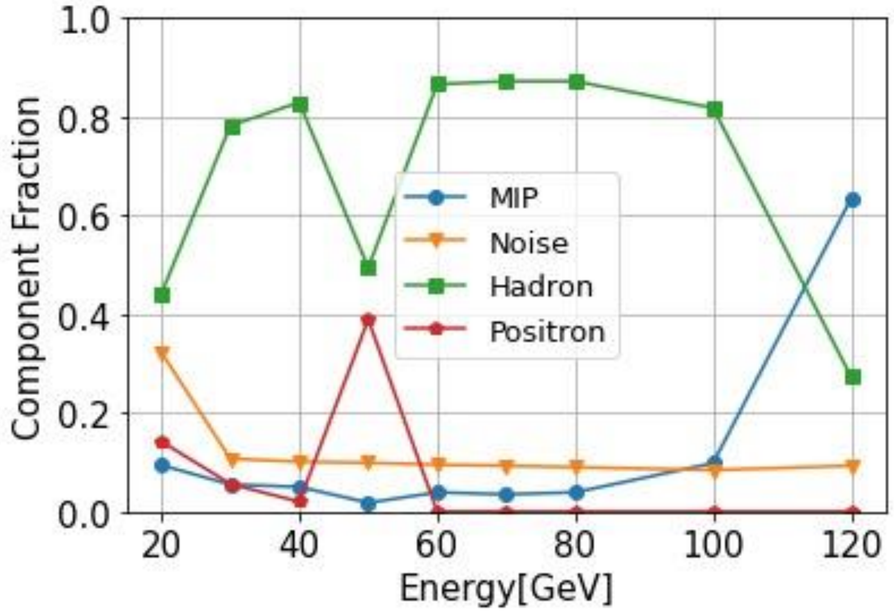




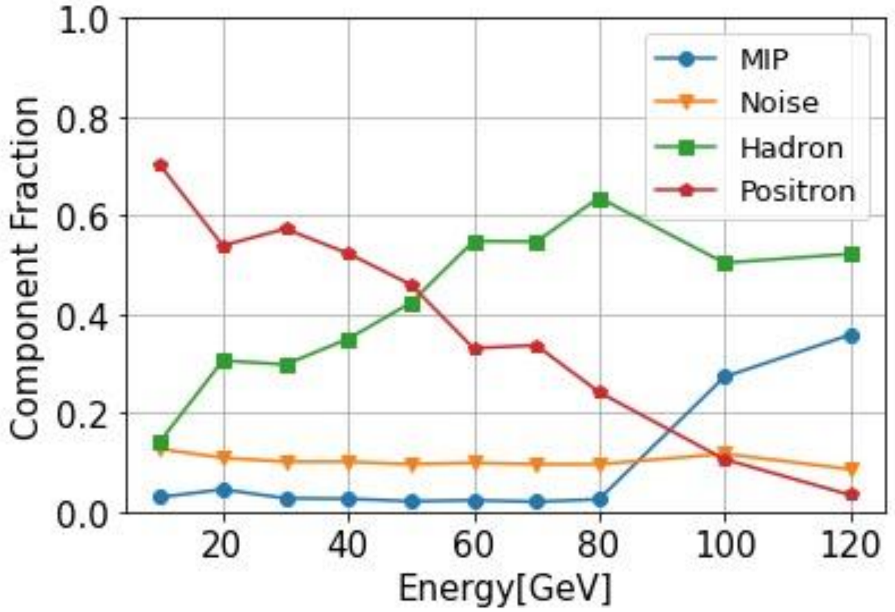
2022 SPS-H8 beam purity: preliminary results

- Imaging calorimeter: characteristics of hit patterns with $\mu^+/e^+/\pi^+$
- Positron beam: largely dominated by hadrons, barely no positrons >60 GeV
- Hadron beam: a considerably large fraction of positrons (esp. with lower energy)

2022 SPS-H8 positron beam data



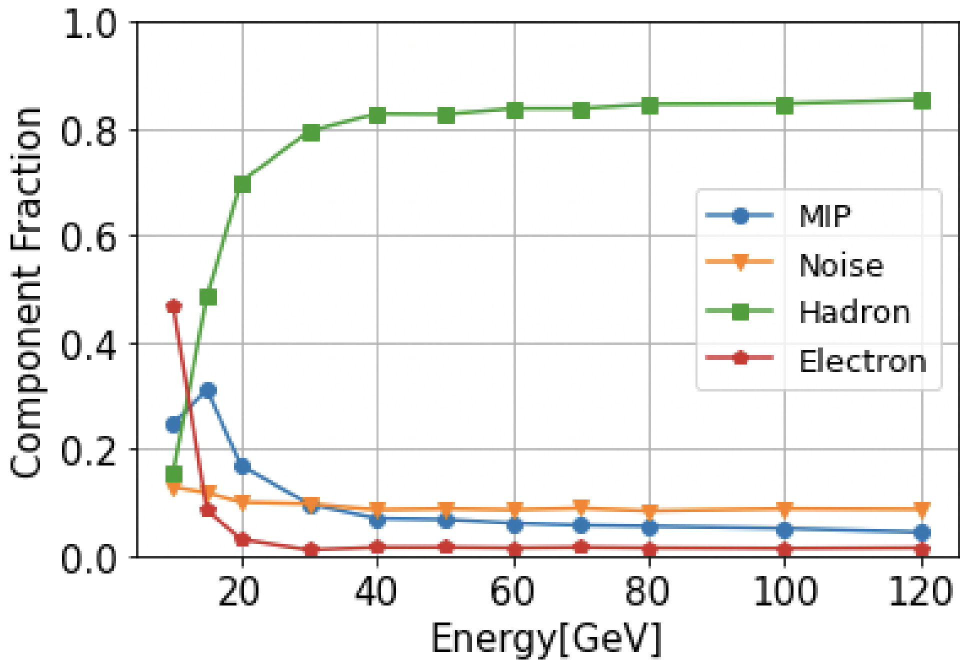
2022 SPS-H8 hadron beam data



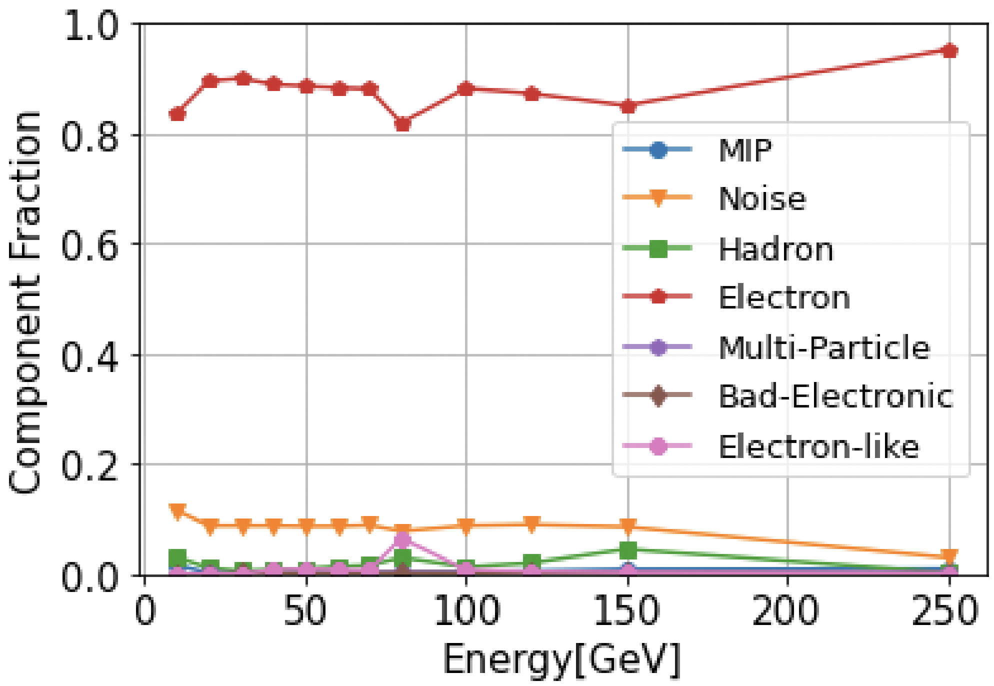
PID studies with fractal dimension

- SPS-H2 beam purity >80% for electron and pion beams >30 GeV
- Significantly better beam purity at H2 than H8
- Noise events now become a dominating factor: ongoing studies

SPS-H2 Pion Beam

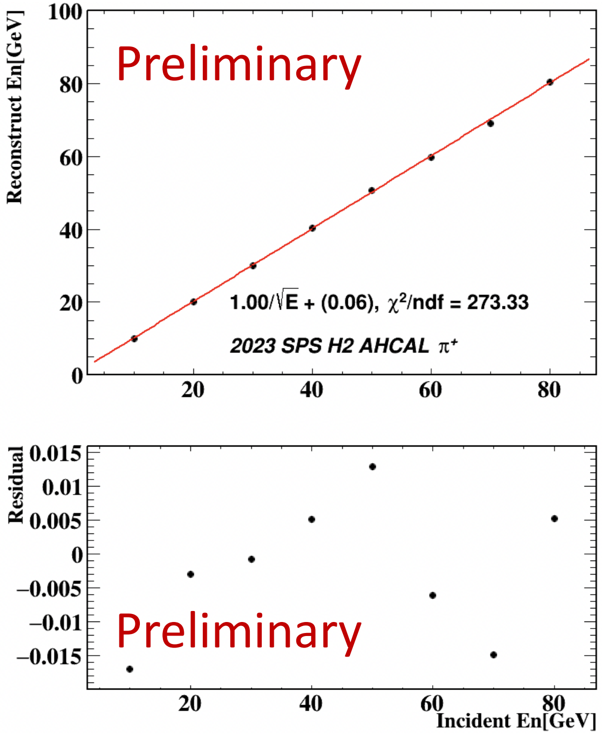


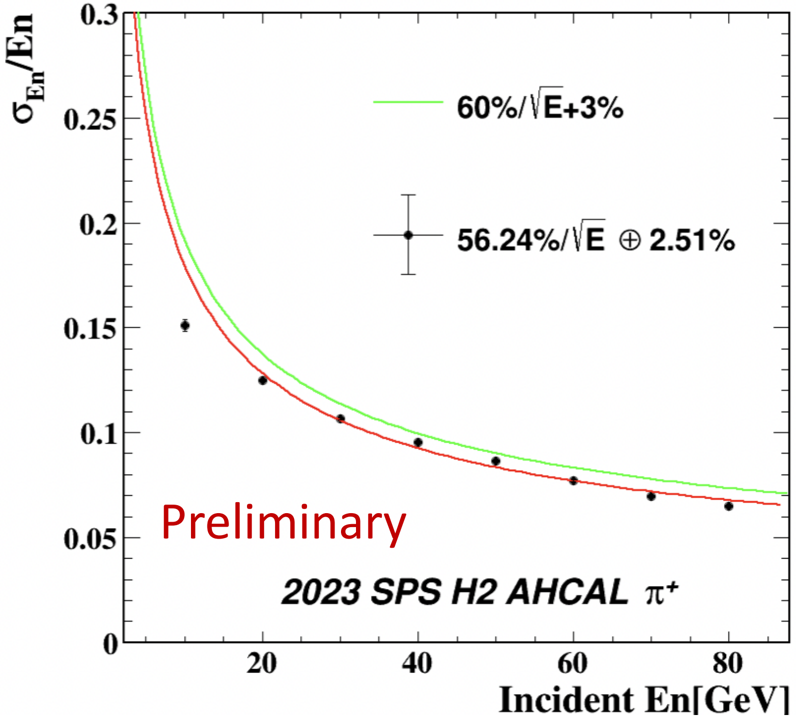
SPS-H2 Electron Beam



AHCAL performance: preliminary results

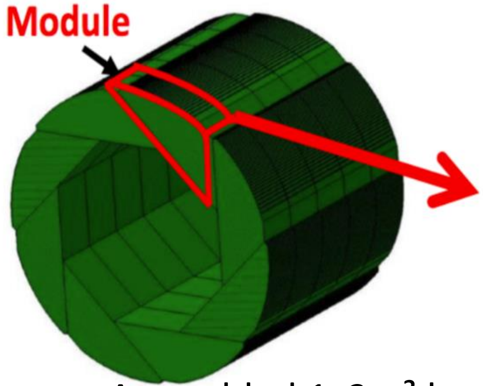
- AHCAL prototype (alone) using data sets after PID selections
  - Energy linearity within $\pm 1.5\%$
  - Energy resolution $56.2\%/\sqrt{E(GeV)} \oplus 2.5\%$ (expected $60\%/\sqrt{E(GeV)} \oplus 3\%$)



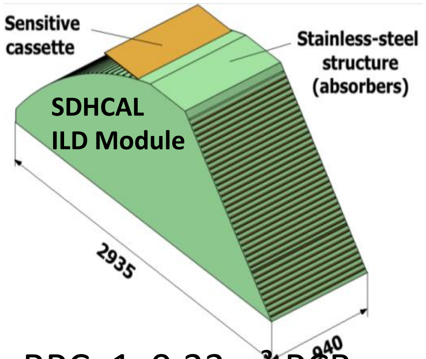


Ongoing studies to address critical issues : non-linearity effects and corrections (SiPMs, ASICs), MC validation

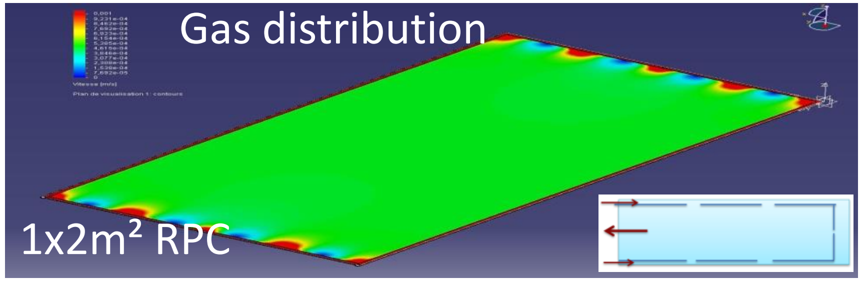
CALICE SDHCAL option



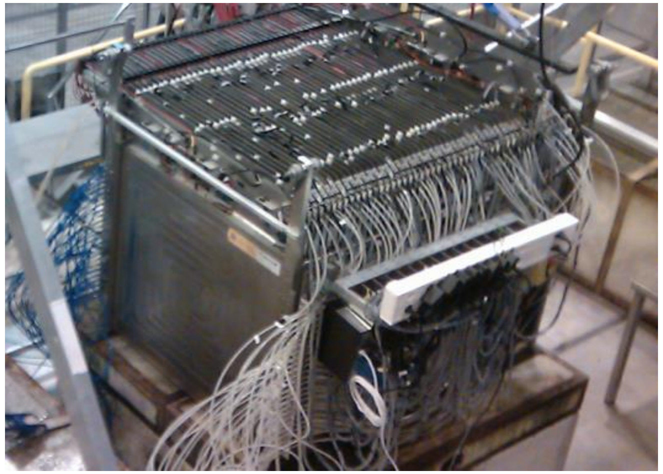
GRPC: Glass Resistive Plate Chambers



Assembled 1x2m² large RPC, 1x0.33m² PCBs



Semi-Digital HCAL prototype：glass RPC, steel



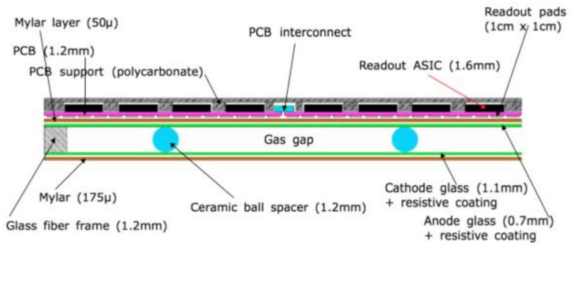


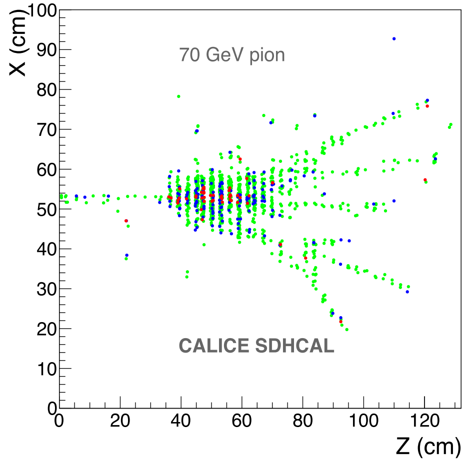
Figure 1. A schematic cross-section of a SDHCAL active layer (not to scale).

Published: JINST 10 (2015) P10039

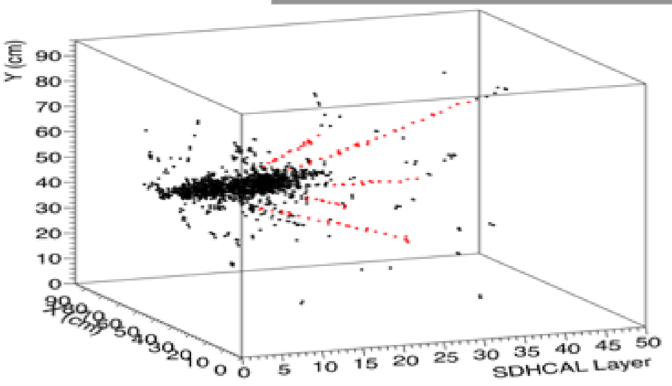
CALICE SDHCAL prototype (since 2012)

- 48 longitudinal layers (~6λ_I), each layer of 1×1 m^2
- Transverse granularity 1×1 cm^2
- 6912 ASICs (“HARDROC”, 64-ch)
  - 3-threshold, ~440k readout channels
- Capable to run in power-pulsing mode (Linear Colliders)

SDHCAL performance



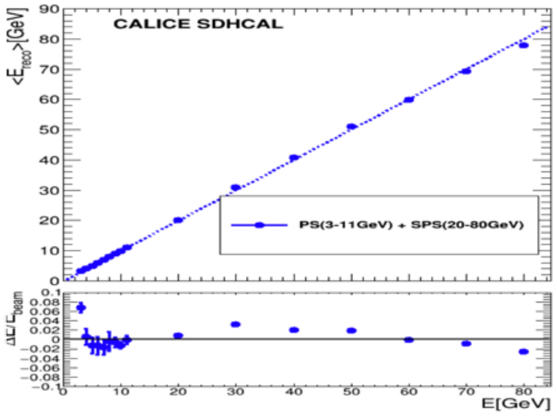
JINST 12 (2017) P05009

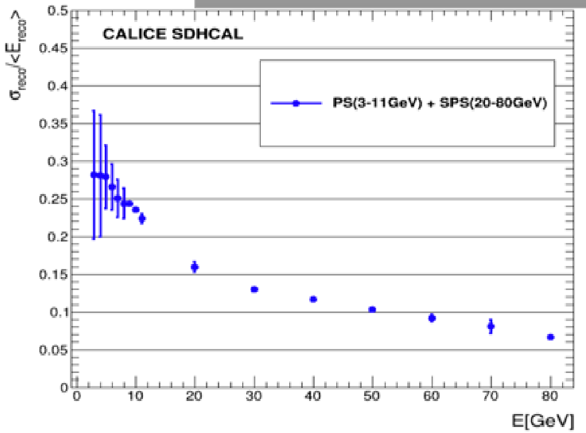


Energy reconstruction

JINST 11 (2016) P04001

JINST **17** (2022) P07017

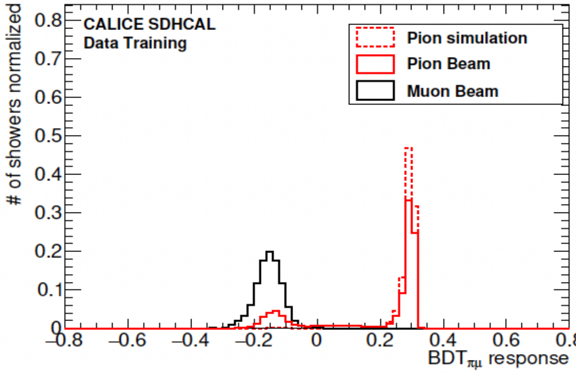


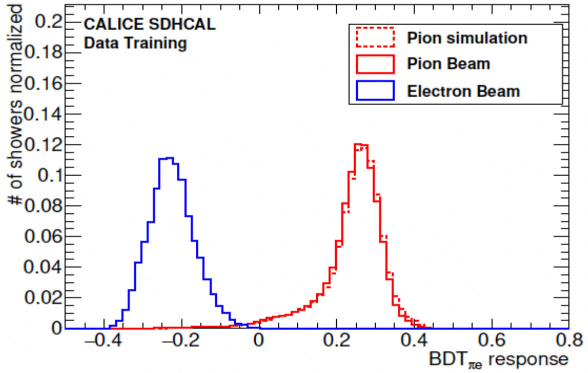


- SDHCAL prototype tested several times with beams during 2012 – 2022 at CERN PS and SPS
- The threshold information helps to improve on energy reconstruction (multiple hits in one pad)
- Detailed beamtest studies on hadronic showers
  - Energy reconstruction
  - Particle identification: electron/muon/pion
  - Track segments: reconstruction by 3D-Hough transform

Particle identification

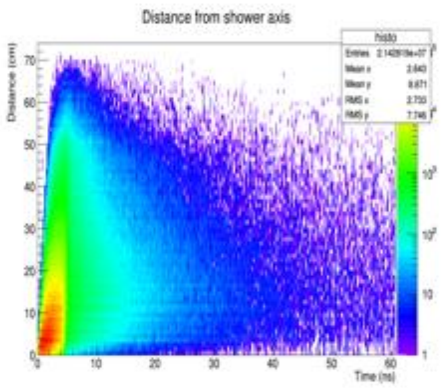
JINST 15 (2020) P10009

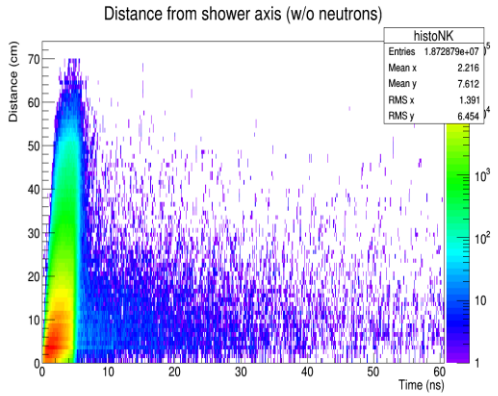




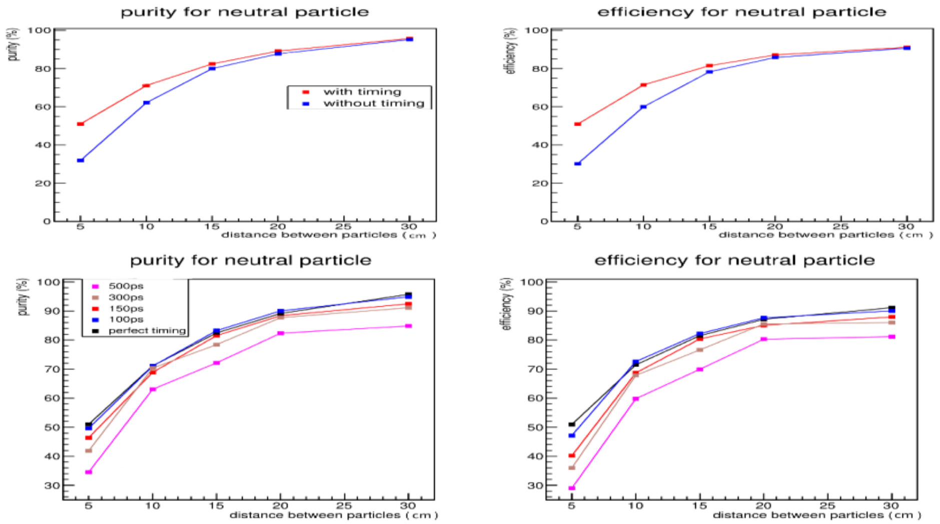
T-SDHCAL: precision timing with SDHCAL

Timing is an important factor to identify delayed neutrons and **better reconstruct their energy**

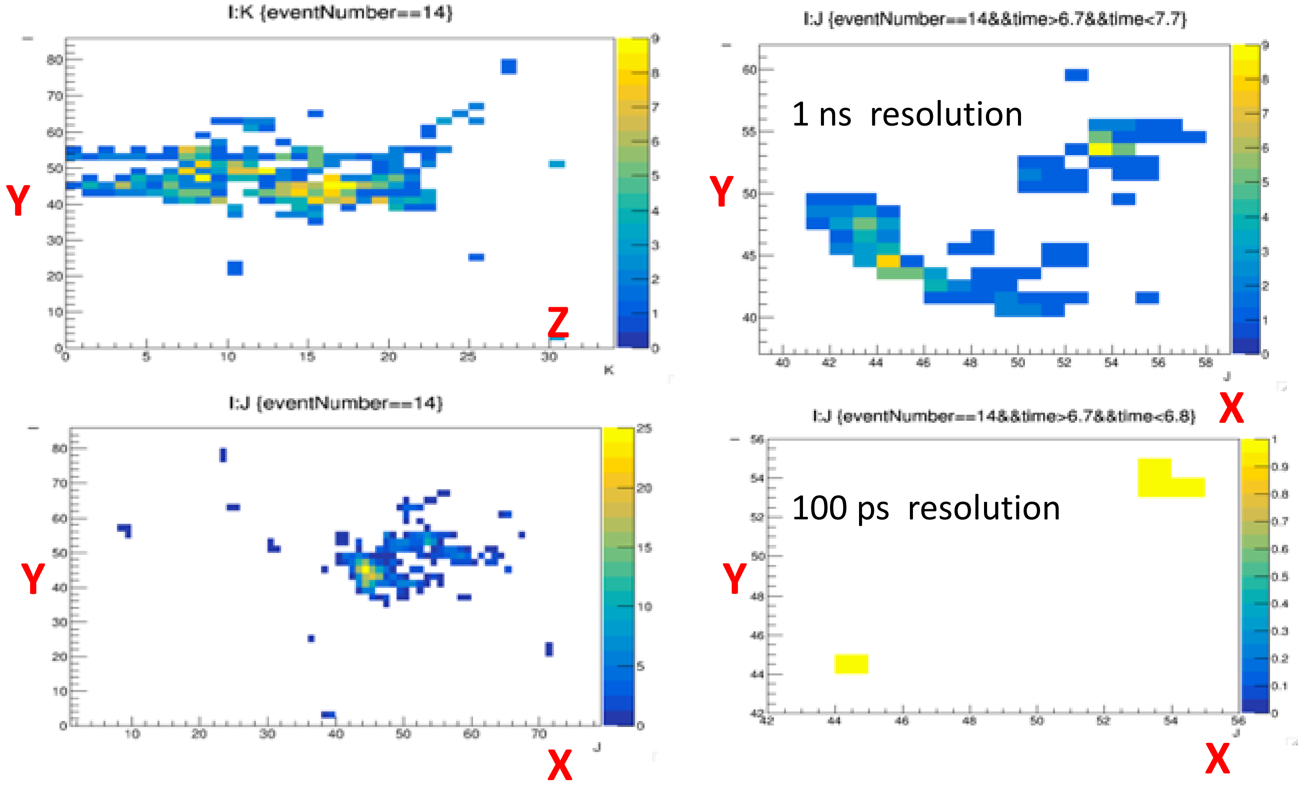




PFA separation with/without timing



Timing can help to separate close-by showers and reduce the confusion for a better **PFA** application. Example: pi-(20 GeV), K-(10 GeV) separated by 15 cm.

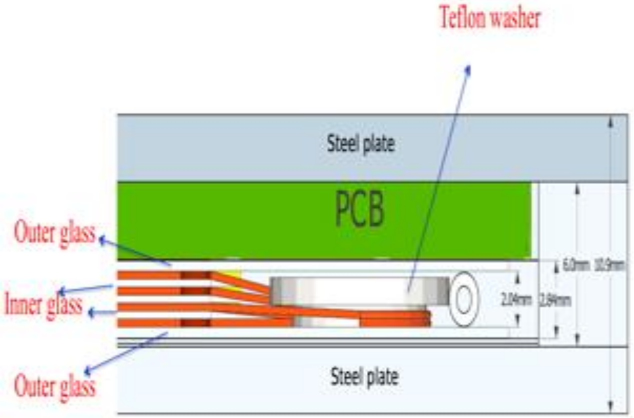


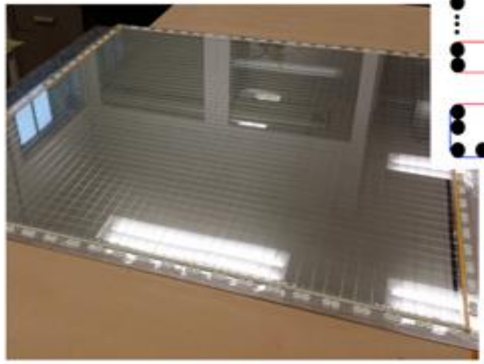
Including time information in the simulation to separate hadronic showers (10 GeV neutral from 30 GeV charged particles) using techniques similar to Arbor

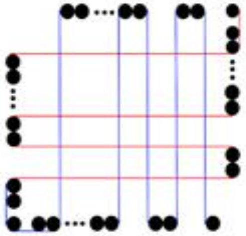
T-SDHCAL: Multi-gap RPC

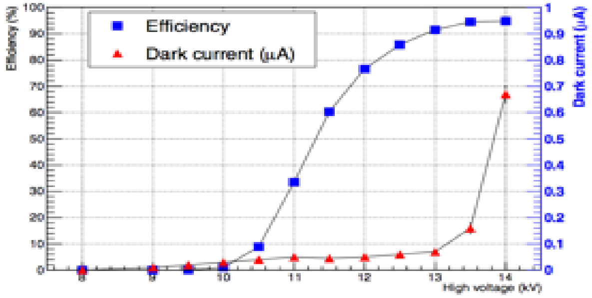
Multi-Gap RPC is an excellent candidate.
5-gap of 200 µm each separating glass plates of 250 µm thick can provide a time resolution of around 100 ps

The standard method to build MRPC is based on using fishing line



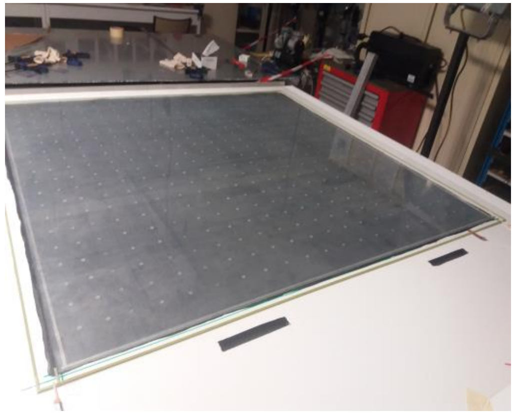






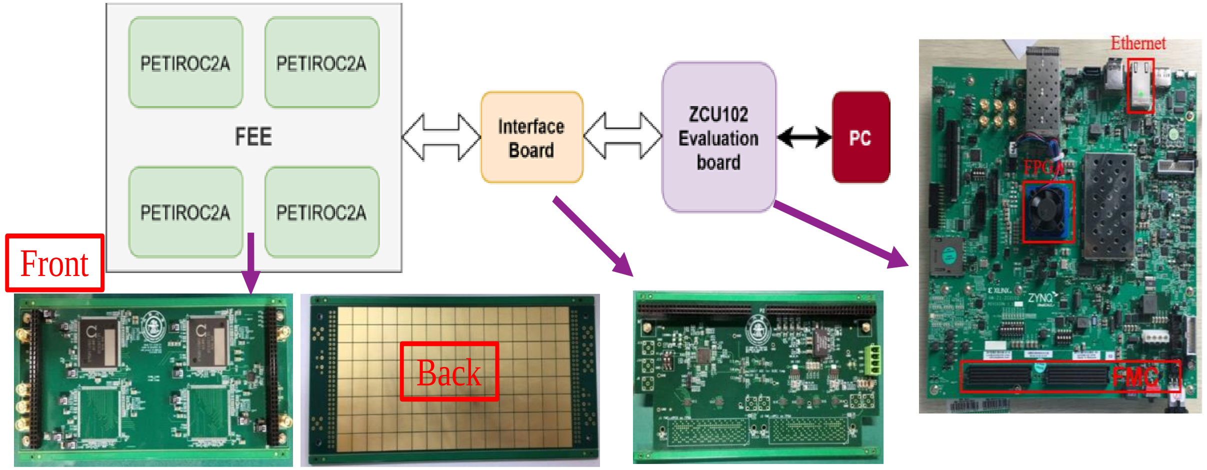
Threshold sets at 114 fC

New and easy way of construction MRPC. Preliminary results show an efficiency > 93% with 5 gaps



T-SDHCAL: readout boards

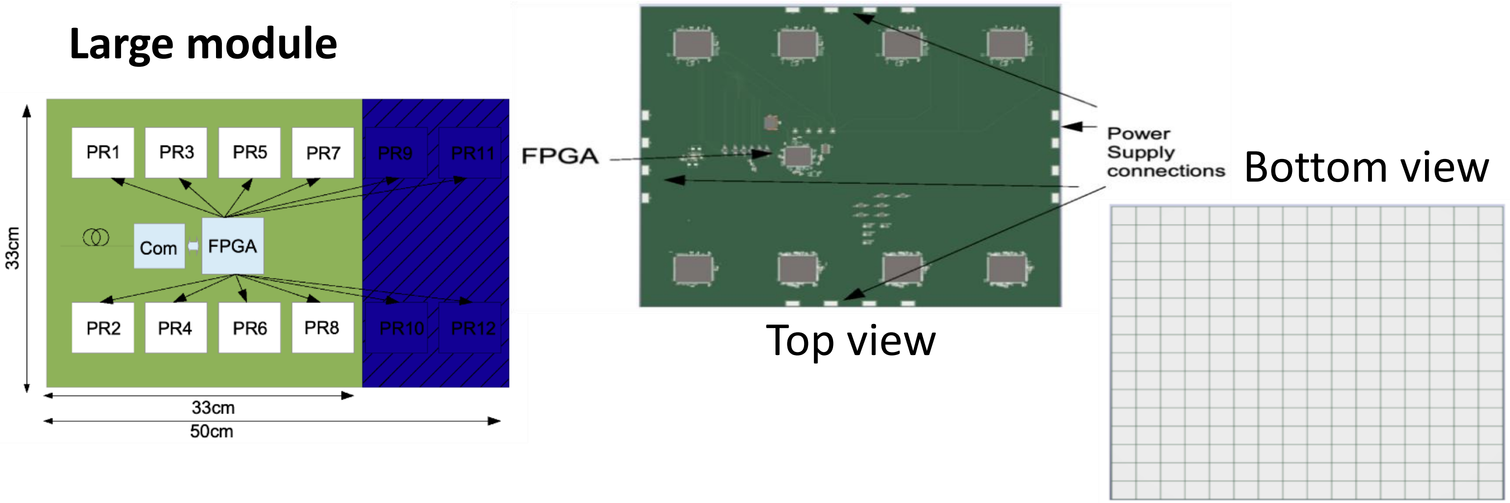
Small module A board with 4 PETIROCs, 128 pads as well as the whole DAQ system was developed and being tested



- Front-End Electronics for MRPC readout with high timing resolution
- The system includes a front-end board (FEB), a detector interface card (DIF) and a data acquisition system(DAQ) based on ZCU102.

PETIROC: 32-channel, high bandwidth preamp, <3 mW/ch, jitter < 20 ps @ Q>0.3 pC (internal TDC of 50 ps time resolution)

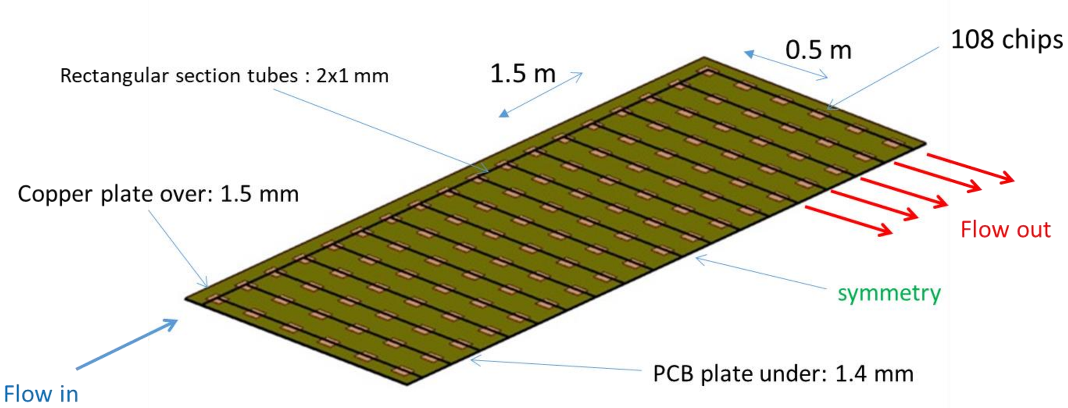
Large module

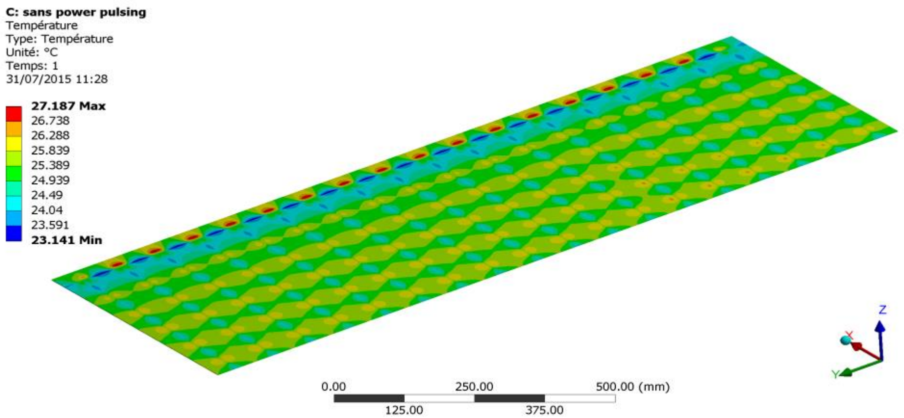


- Board with 8 (could be extended to 12) Petircoc2B ASICs
- Pads 2cm x 2cm, 256 channels
- Local FPGA (Xilinx Spartan-6 TQFP) embedded on board

SDHCAL other R&D activities

- High-Rate capability
  - (M)RPC low-rate capability: could be significantly increased by developing low resistivity materials
  - Doped glass (by Tsinghua group) could be a solution: PVdF ($10^{11} - 10^{12} \Omega \cdot \mathrm{cm}$), PEEK ($10^{8} - 10^{9} \Omega \cdot \mathrm{cm}$) are very stable and chemically inert thermoplastic
- Large SDHCAL module: active cooling scheme for circular colliders
  - Duty cycles of CEPC/FCCee are different from ILC →no power pulsing
  - Working on a simple cooling system using water circulating into copper pipes
  - (Simulation) Temperature distributions within 1.5×0.5 m^2
- New friendly gases: to replace TFE and SF6 for (M)RPC
  - TFE → HFO1234ze, SF6 → Nova4710
  - Developing techniques of recycling gas mixture and recovering exhaust gases





Summary and prospects

- PFA-oriented calorimeters
  - Aim for unprecedented jet energy resolution
  - Various options explored within the CALICE collaboration
  - Active R&D area with steady progress made in past years
  - Successful beam test campaigns with invaluable data samples for EM/hadronic performance evaluation and detailed shower studies
- Gradually moving to ECFA DRD-on-Calorimetry (DRD6)
  - Synergies with other DRD collaborations, e.g. DRD1 (gaseous detectors), DRD3 (semi-conductors), DRD4 (photo-sensors), DRD7 (electronics)
  - First DRD6 Collaboration Meeting at CERN (Apr. 9 – 11, 2024)

Stay tuned: DRD6 overview talk by Roberto Ferrari in the 2nd calorimeter session of this workshop

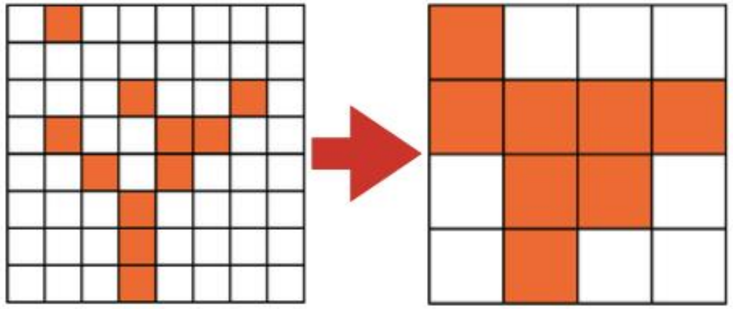
Thank you!

Backup

Fractal Dimension

Particle Identification

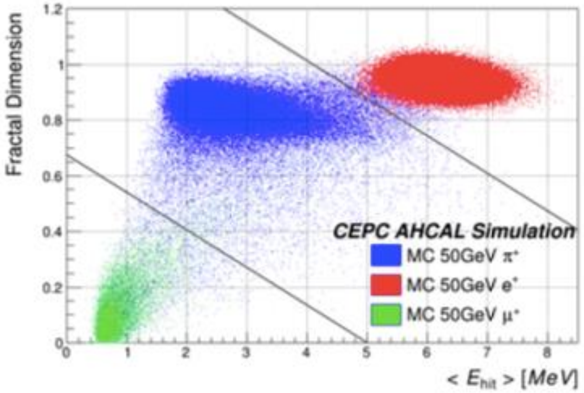
- **Cut-based PID:** FD vs $< E_{Hit} >$
  - $\mathrm{FD} = \left\langle \frac{\log(R_{\alpha,1})}{\log(\alpha)} \right\rangle$, where $R_{\alpha,1} = N_1/N_\alpha$
  - N_α: number of hits scaled by α
  - $< E_{Hit} > = E_{dep}/N_{hit}$



Take $\alpha = 2$ as an example

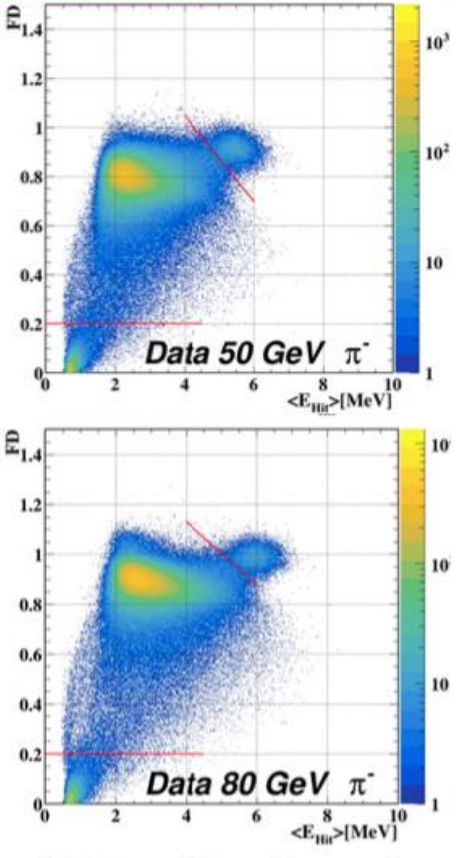
Efficiency @ 50 GeV MC

Truth \ ID	μ^+	π^+	e^+
μ^+	99.4%	0.6%	0
π^+	3.6%	94.1%	2.3%
e^+	0	0.3%	99.7%



Achieved Promising separation power on MC samples.

FD Ref: PhysRevLett.112.012001



Work on Pion Beam data

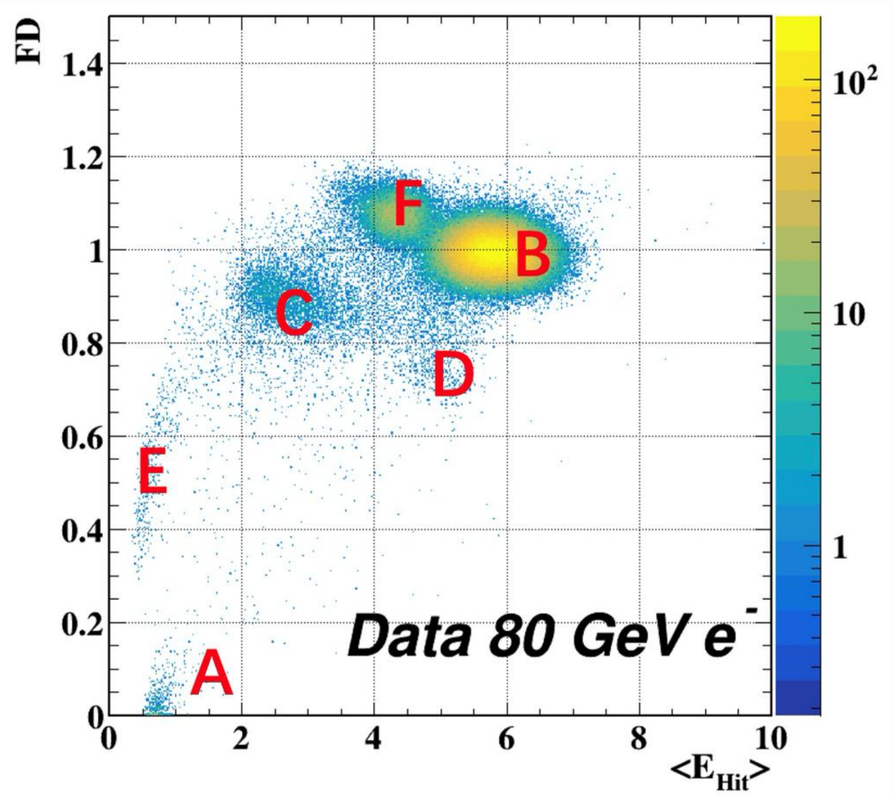
Oct 26, 2023 Siyuan Song (siyuansong@sjtu.edu.cn), SJTU. The 2023 International Workshop on CEPC 16

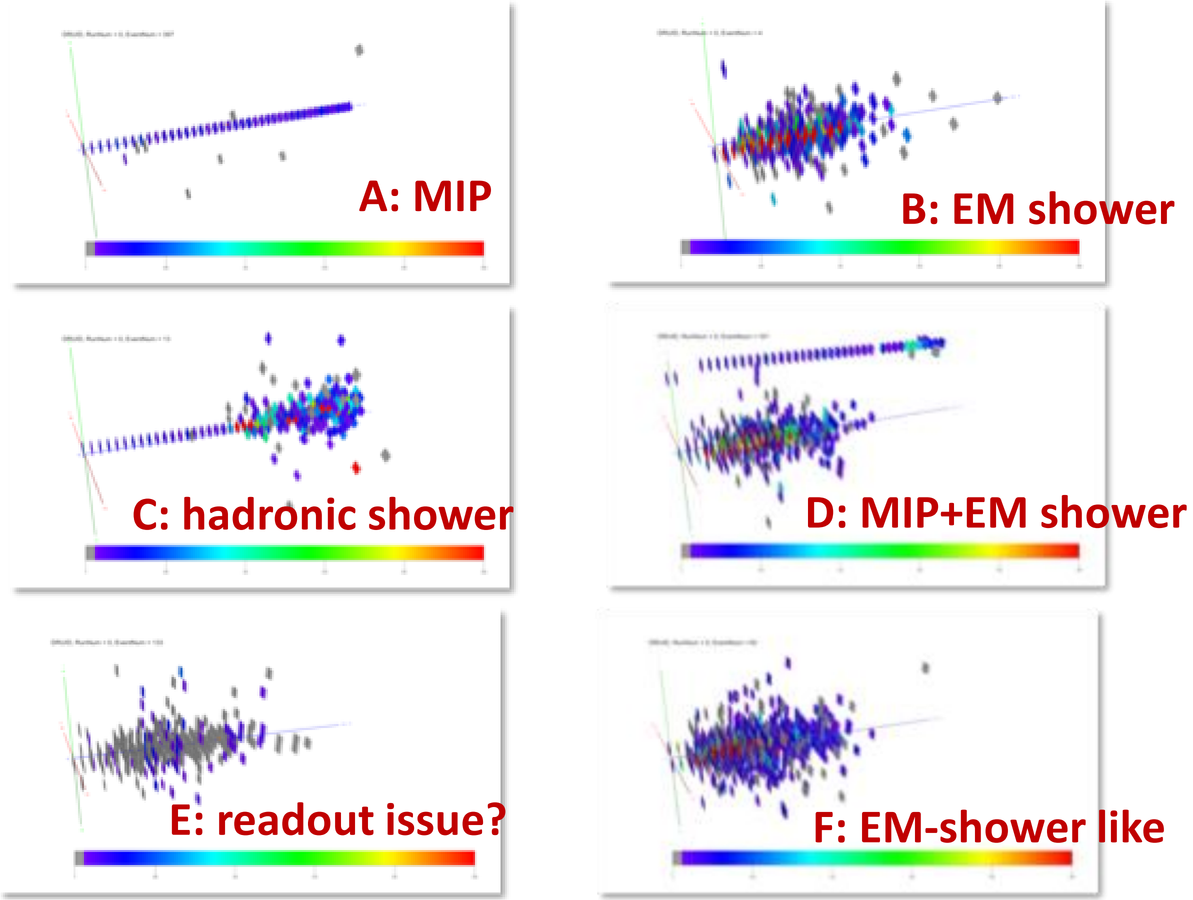
Self-similar pattern of particle showers in transverse direction

PID studies with beamtest data

Xin Xia (IHEP)

- Characteristics of Fractal Dimension (FD) with different beam particles
  - Only possible with imaging calorimeter (high granularity)

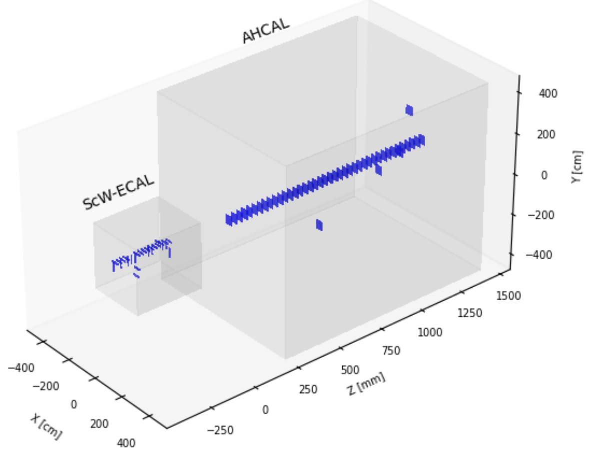




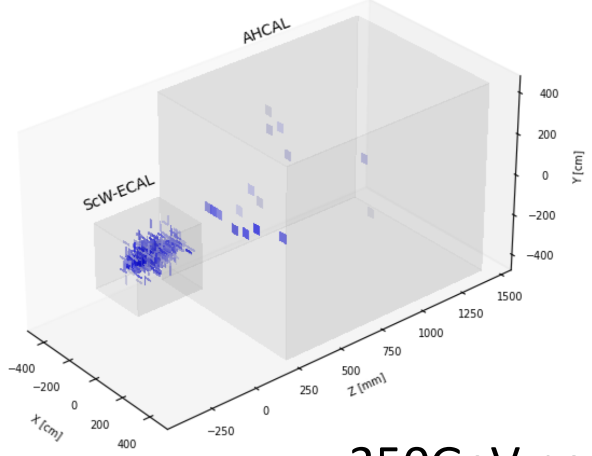
FD methodology based on
M. Ruan et al., Phys. Rev. Lett. **112**, 012001

Event display with ScECAL+AHCAL

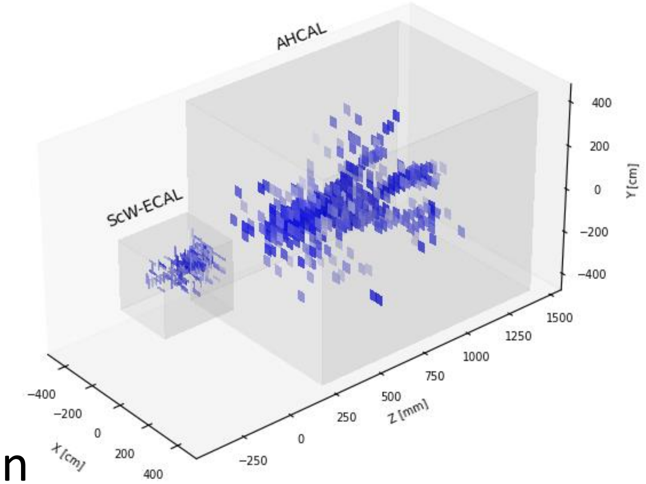
100 GeV mu-

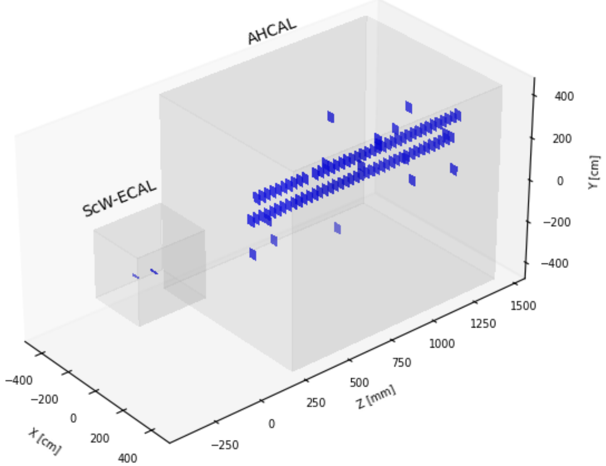


60GeV electron

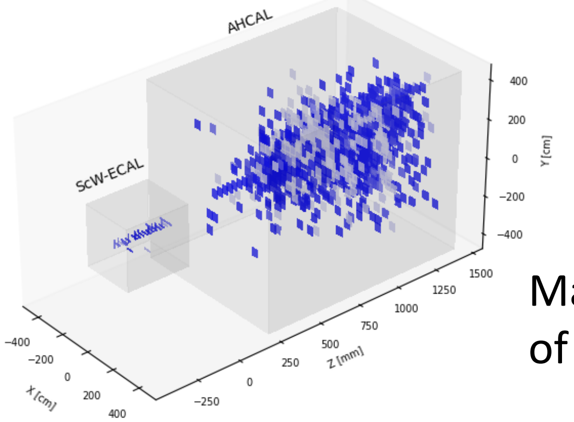


60GeV negative pion





350GeV negative pion



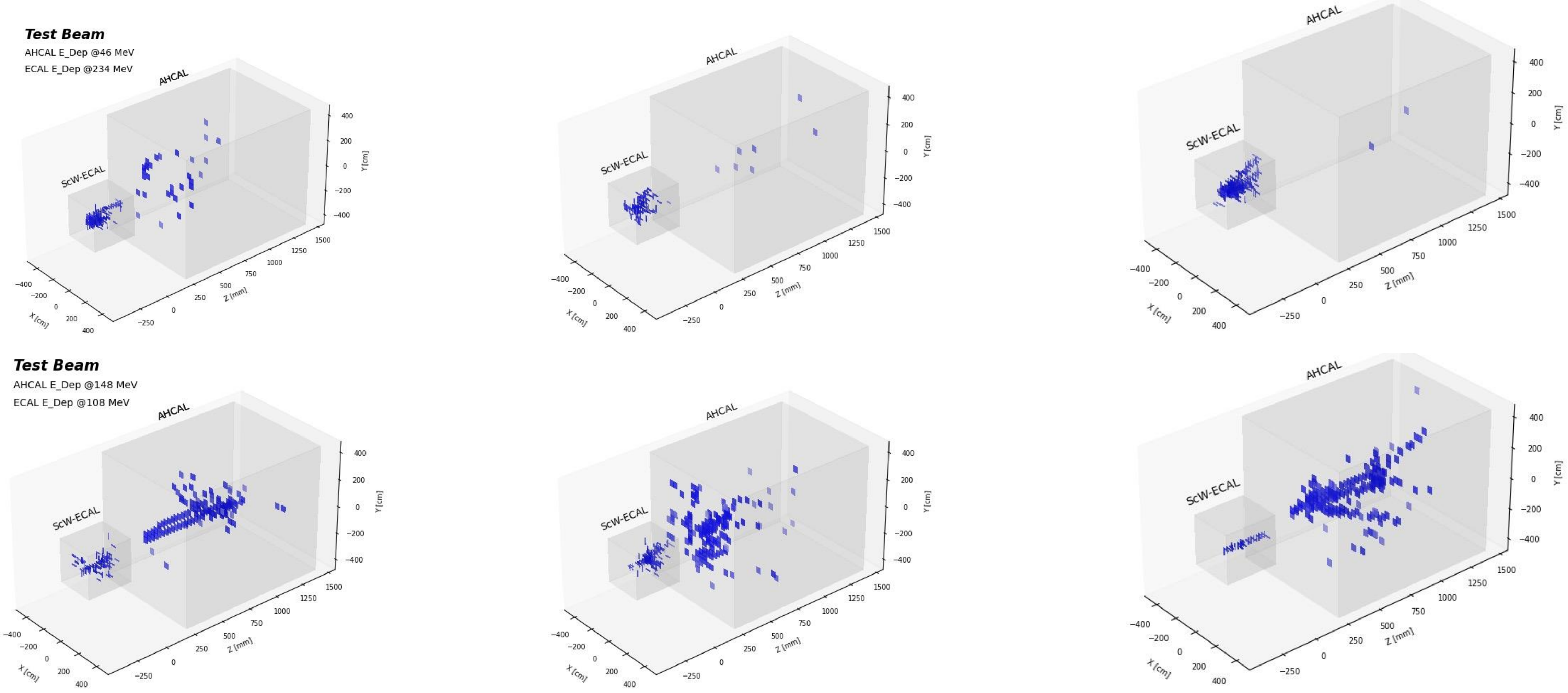
Maximum pion beam energy of existing testbeam facilities

One run of different position scans: muon beam out of ScW-ECAL acceptance

Impressions: much better purity of electron and pion beams than data taken at H8 in 2022

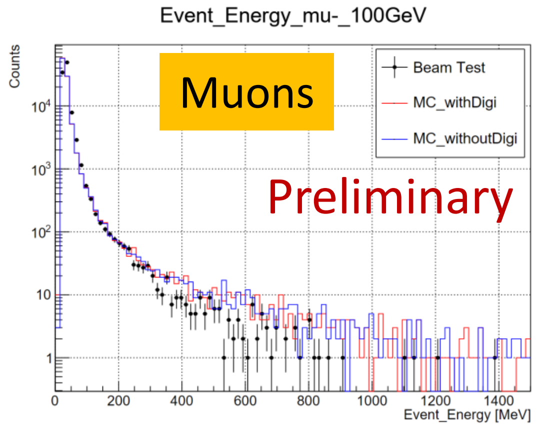
Hadronic showers in ECAL+HCAL at PS

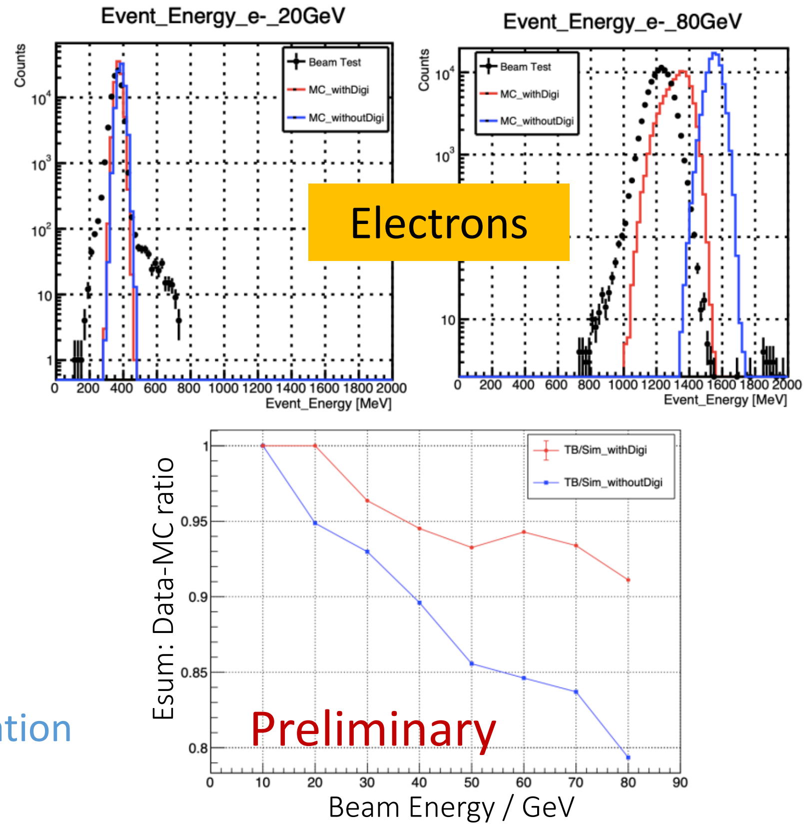
5 GeV π^- | 10 GeV π^- | 15 GeV π^-

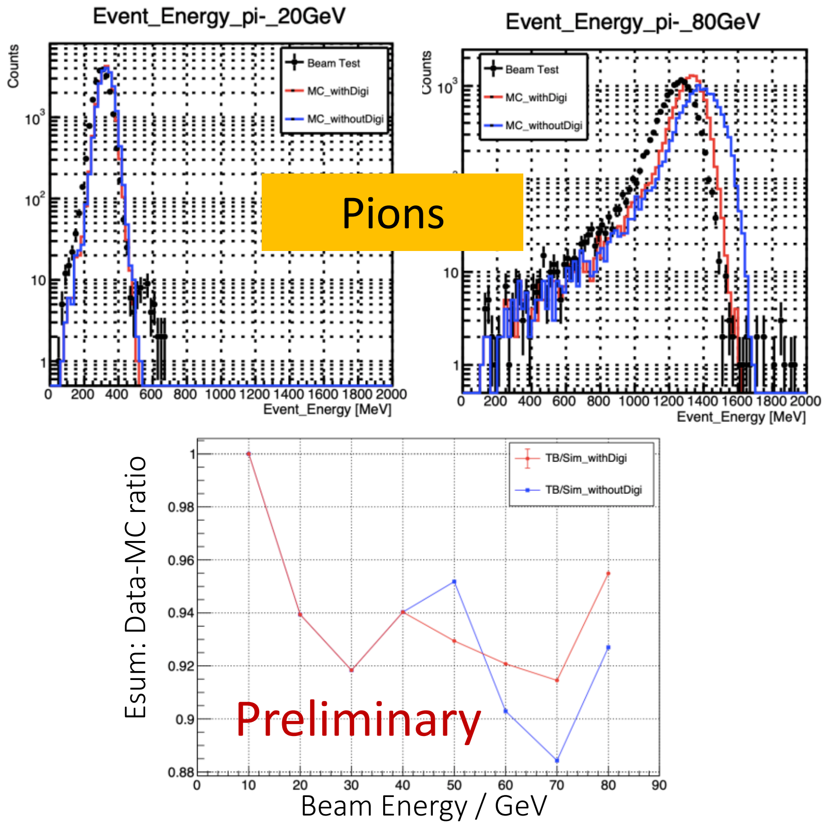


Beamtest data: ongoing studies

- Ongoing studies to address critical issues
  - Non-linearity effects and corrections: saturations in SiPM and ASIC with large signals
  - MC validation with electron and pion data: to improve MC/data consistency



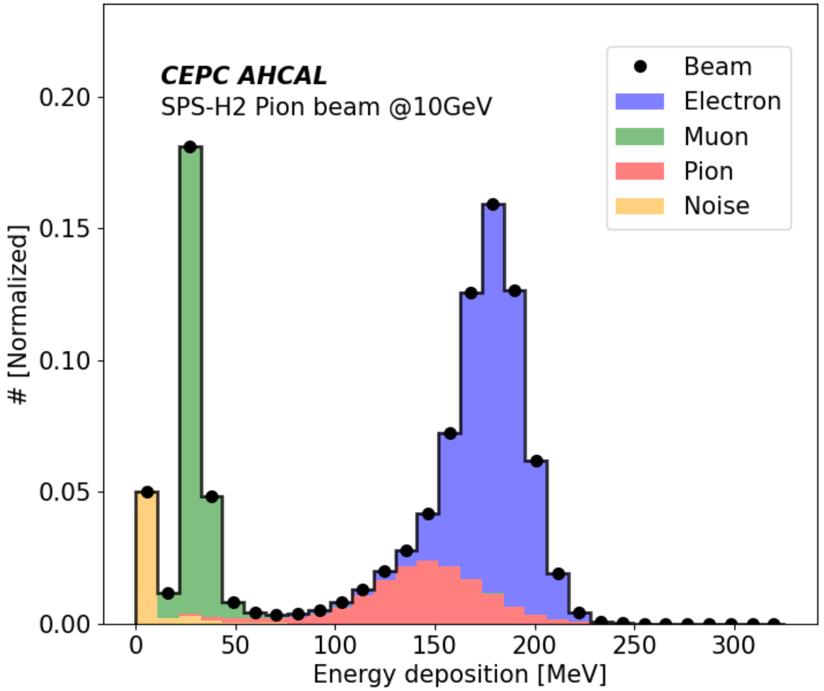


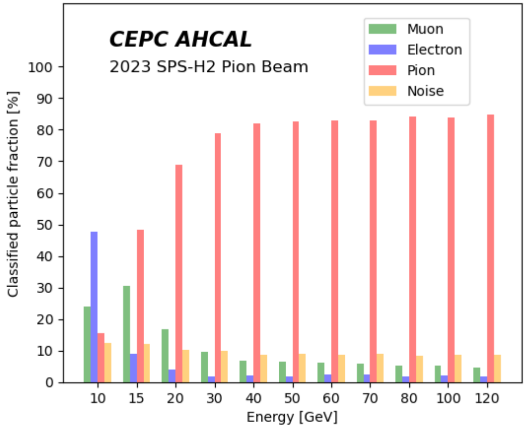


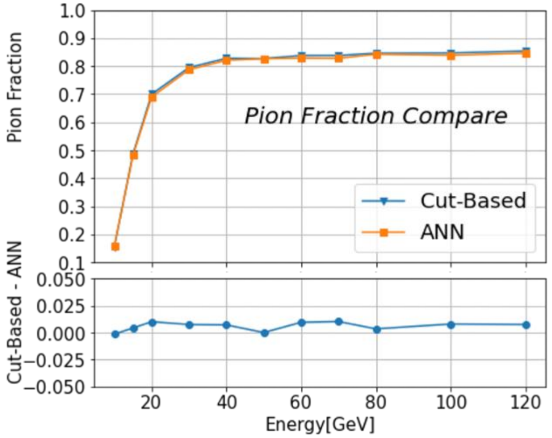
MC: Geant4 simulation w/wo digitisation for scintillator-SiPM and ASIC

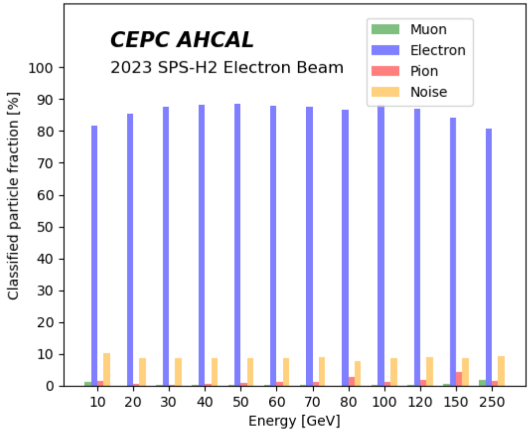
PID studies with ANN

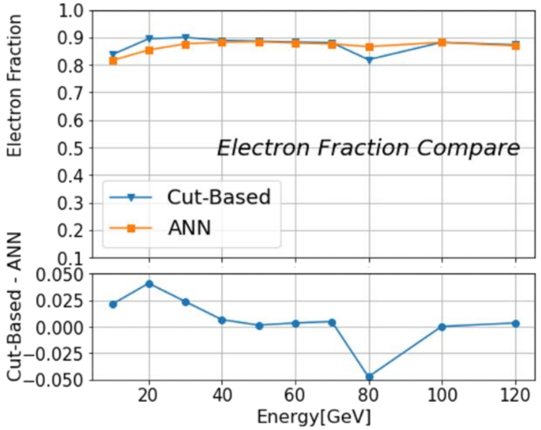
- **PID based on ANN (ResNet): input tensor of energy deposition per AHCAL tile**
- ANN results mostly consistent with Fractal Dimension (FD results)
  - Pion beam: difference within 1%; electron beam: within 5%











ResNet: He K, Zhang X, Ren S, et al. "Deep residual learning for image recognition" Proceedings of the IEEE conference on computer vision and pattern recognition. 2016: 770-778